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TECHNICAL NOTE 3295

EFFECT OF PRESSURE ON THERMAL CONDUCTANCE OF CONTACT JOINTS

By Martin E. Barzelay, Kin Nee Tong, and George F. Holloway

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SUMMARY

As an extension of previous experimental work further tests were conducted to determine the factors influencing the thermal conductance across the interface formed between stationary plane surfaces of 75S-T6 aluminum-alloy and AISI Type 416 stainless-steel blocks. The types of joints investigated included bare metal-to-metal contact, contact surfaces separated by a good conductor (brass shim stock), and contact surfaces separated by a thin sheet of insulation (asbestos). The average surface roughness of the metal blocks ranged from 10 to 120 microinches root mean square at the interface. The plane areas forming the interface were surface ground to an average flatness of ±0.0002 inch. The average contact pressure on the interface-joint area varied from approximately 5 to 425 psi. The mean temperature of the interface was held to within ±5° of 200°, 300°, and 400° F. Heat flows of 7,000 to 80,000 Btu per square foot per hour produced temperature drops across the interface of from less than 1° F to as much as 150° F for some special bare joints and to about 200° F for the insulating types of joints.

INTRODUCTION

In reference 1, the effect of heat flow, temperature drop, temperature level, and surface condition on the thermal conductance across interface joints was experimentally determined. The materials of major concern were 75S-T6 aluminum alloy and stainless steel.

In the present investigation the experimental work of reference 1 is extended to include pressure as a variable influencing interface conductance. The introduction of high pressure helped to clarify a number of points not fully understood previously. As a result of a more positive surface contact due to substantial pressure, findings related to material properties, surface roughness, surface flatness, and temperature level became more coherent. The pressure parameter thus gave a new means to explain important trends and also cast a new light on the complex physical phenomena of heat transfer across discontinuous metal joints.

The principal materials chosen for specimens were stainless steel and 75S-T6 aluminum alloy as in the previous investigation. Although it was realized that 24S alloys are better suited for present-day, high-temperature applications than 75S alloys, the latter material was chosen to obtain results that can be compared with those of reference 1 and with other available data.

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SYMBOLS

h	thermal conductance of interface, $Q/\Delta t$, Btu/(hr)(sq ft)($^{\circ}$F)
K	thermal conductivity, Btu/(hr)(ft)($^{\circ}$F)
p	average interface pressure, psi
Q	heat flow, Btu/hr/sq ft
t	temperature, $^{\circ}$F
t_m	mean interface temperature, $^{\circ}$F
t_m'	nominal mean interface temperature, $^{\circ}$F
Δt	temperature drop across interface, $^{\circ}$F
x	distance in direction of heat flow, ft

DESCRIPTION OF APPARATUS

The apparatus used in this investigation was the same as that described in reference 1 with the addition of a lever system to apply compressive loads to the specimen and with several minor modifications described in the following sections.

Lever System

The lever system is shown in figure 1. It was designed to apply compressive loads, in increments up to 425 psi, to the interface contacts under study. In constructing the lever system, special care was taken to insure an axial load on the entire assembly which formed a relatively slender column. Axial loading was attained as nearly as possible through use of a locating pin, projecting through the fire-brick insulation, which determined the positioning of the horizontal loading pin.

Modifications

No substantial changes were made in the previously used apparatus. The minor modifications were as follows:

Automatic timer.- An automatic timer was used to control the radio-frequency heater by cyclic switching within the same 120-second on-off cycle as in the previous experimentation.

Aluminum heating head and heat meter.- The stepped cylinder that matched the stainless-steel cylinder and made up the lower part of the heating head was changed from copper to 2S-0 aluminum. It was found previously that the radio-frequency skin effect and the high temperature caused rapid corrosion and peeling of the copper. No satisfactory method of plating was found to eliminate these effects. The 2S-0 heating head, on the other hand, was practically unaffected after long heating periods.

The pure copper heat meter of the previous tests was also replaced by one made of 2S-0 aluminum. This substitution not only eliminated the previously mentioned corrosion and plating problem but it also facilitated calculations since the thermal conductivity of 2S-0, unlike that of the pure copper, was virtually constant over the temperature range encountered.

TEST PROCEDURE

The test procedure in this investigation was similar to that of reference 1 but with modifications as a consequence of applying pressure to the interface. Although there was no change in the theoretical basis of the tests, this section will be repeated for ready reference.

Theoretical Basis

From the basic Fourier equation, the steady-state heat flow at any part of the heat path is given by

$$Q = K \frac{dt}{dx} \tag{1}$$

If the thermal conductance of the interface is defined as

$$h = \frac{Q}{\Delta t} \tag{2}$$

then

$$h(\Delta t) = K \frac{dt}{dx} \tag{3}$$

or

$$h = \frac{K \frac{dt}{dx}}{\Delta t} \tag{4}$$

The temperature at the boundary of a specimen can be obtained by extrapolating the temperature-distance relation existing in the interior of the specimen. The temperature drop across the interface Δt is thus determined. In equation (4) the product $K \frac{dt}{dx}$ is the heat flow per unit area. This can be obtained by measuring the temperature gradient in the 2S-O aluminum heat meter and multiplying this gradient by the conductivity of the aluminum.

Description of Specimens

The test specimens which were used to provide the interfaces for testing were 75S-T6 aluminum-alloy or AISI Type 416 stainless-steel blocks 3 inches in diameter and approximately 1 inch thick, as in reference 1. The faces were surface ground to specified root-mean-square roughness on a Blanchard surface grinder. All specimens of the same roughness were machined simultaneously with one single setup on the grinder; therefore the roughness and flatness values were nearly the same within such a group of specimens. The root-mean-square roughness was checked, both before and after the tests, by a Brush surface analyzer equipped with a root-mean-square indicator, and the flatness, by comparison with a standard surface plate.

Pertinent information concerning individual specimen pairs is given in table I.

Thermocouple Technique

Local temperatures were determined in the specimens and the heat meter by means of iron-constantan thermocouples made of Brown and Sharpe gage 30 wire. After the thermocouple bead was formed by a direct-current arc welder, the length of bare and insulated lead which was to lie within the specimen was dipped in Glyptal lacquer to provide insulation. The thermocouple was then inserted into a 0.046-inch hole drilled radially in the specimens to $\frac{5}{8}$-, 1-, or $1\frac{1}{2}$-inch depth and filled with wet copper dental cement which when set served to hold the thermocouple firmly in place and provide good heat transfer. To insure additional strength of the fine leads a $\frac{1}{4}$-inch length of the outside insulation was inserted in the hole countersunk for the purpose. The point of entry of the leads was also reinforced by silicone rubber.

The thermocouples were placed at one or two transverse sections in the heat path in each of the two specimens. The transverse section nearest the interface was located at either 0.100 or 0.050 inch from the interface. In most cases this one station was sufficient because the relationship between the temperature gradient in the heat meter (measured over a distance of 3.75 inches) and that in the specimens had been established by a large number of previous tests. A second station along the heat path, however, made it possible to check the temperature gradient when it was desirable.

The number of thermocouples used at one level varied from two to six, placed at different radial distances and angular positions. The use of thermopiles was abandoned because it was felt to be more important to detect any unevenness of temperature distribution as revealed by individual readings than to obtain a greater sensitivity.

Conduct of Tests

The equipment was assembled as shown in figure 1. All interface junctions were thoroughly cleaned with acetone. Thin aluminum foil was placed between all contact surfaces, except the interface to be tested, to reduce undesirable temperature drops. All interfaces were then sealed at the periphery with a silicone rubber compound (Silastic 122). This seal prevented any foreign material from entering the interface during testing when the application and removal of load might have jarred the test column. Furthermore, the silicone rubber when hardened between 300° F and 400° F provided a firm nonconducting link for the specimen pairs to be tested, strong enough to maintain their original matching position for further tests. No significant residual tension was retained when the setting took place during an application of pressure to the specimens followed by relief of the load. The silicone rubber was easily removable for new assembly or interface matching.

After setting up the heating column, as seen in figure 1, and filling the containers with diatomaceous earth insulation, the maximum load was applied to flatten the highest points in the interface; the load was then removed and heating started.

The specimens were brought up to the desired temperature gradually and when balance was reached the cyclic switching of the radio-frequency heater kept the mean interface temperature at, or very near, the 200°, 300°, or 400° F levels.

The continuously recorded heating-head temperature gave an indication of the direction of necessary adjustment in the heating cycle for reaching and maintaining a steady-state heat flow through the heat meter and interface. The type and amount of cooling was usually left unchanged during this procedure. There was, of course, a time lag between the temperature variation in the heating head and in the specimens, which occasionally required approximately an hour for the apparatus to reach a static thermal balance. When a steady state was evidenced by constant temperatures for a reasonable period of time, all thermocouple readings were taken in quick succession.

The general sequence of testing was as follows:

(1) 200° F interface, low rate of cooling; four pressures in increasing order (approximately 5, 90, 240, and 425 psi) after which load was completely relieved and the above four points were repeated to check consistency and possible experimental errors

(2) 300° F interface, low rate of cooling; twice at four points as above

(3) 400° F interface, low rate of cooling; twice at four points

(4) 200° F interface, high rate of cooling; twice at four points

(5) 300° F interface, high rate of cooling; twice at four points

(6) 400° F interface, high rate of cooling; twice at four points

In a few cases, in order to investigate the importance of the previous heating-and-loading history of the specimens, the above order was reversed or interchanged.

PRECISION OF DATA

The possible sources of errors in this investigation were generally the same as those discussed in reference 1. The radial heat losses through the insulation, previously considered insignificant, were measured in a number of representative tests and were found not to exceed 5 percent of the measured heat flow under the worst conditions (such as low contact pressure and poor interface conductance). This error would result in the same percentage of error in the conductance values, but it was decided that corrections were unnecessary, since the error is always in the same direction and does not influence the relative magnitude of the results.

Although thermocouples were placed as close as possible to the interface (0.100 or 0.050 inch), a linear extrapolation of the axial temperature gradient could have been inaccurate when this gradient was large, when the temperature drop was unusually small, or when a radial gradient of sufficient magnitude was present. However, any error due to this extrapolation was assumed negligible.

The conductance, as determined by the heat flow and the temperature drop at the interface, is a value averaged over the entire interface area of approximately 7 square inches. Since the temperature adjacent to the interface was computed by averaging a number of thermocouple readings in the same transverse section, any unevenness of heat flow over the interface, although influencing the conductance value considerably, is not represented as such in the results. It is believed, however, that the thermocouples were so located within one transverse section that a simple arithmetic average provided a good representative temperature value.

The variation in conductivity of the 2S-0 aluminum heat meter in the temperature range utilized was estimated not to exceed 2 percent. The error in the determination of the heat flow and conductance values due to this cause would thus be ±2 percent.

All the above items might influence the conductance value presented to an estimated ±10 percent in the extreme, but it would be very difficult to compute them exactly in each of the hundreds of test runs. There is no danger, however, that the errors were of a cumulative or of a widely fluctuating nature and thus would tend to obscure the trends detected in this investigation.

RESULTS

The results of the tests made to determine the conductance of various interface joints are given in table II. This table records the temperature drop across the interface, the quantity of heat flowing, and the interface conductance for each test for four different pressure levels at each of the three mean interface temperatures chosen. The data of table II are also presented in a series of curves which are discussed below. (See figs. 2 to 11.)

Effect of Surface Roughness

The effect of root-mean-square surface roughness on conductance for 75S-T6 aluminum joints may be seen in figures 2(a), 2(b), 2(c), and 2(f). In figures 2(d) and 2(e) the conductance of interfaces formed between stainless-steel specimens of two different roughnesses is plotted and the results are compared in figure 3. It is apparent that at any pressure level the conductance increases as the root mean square of the surface roughness decreases. However, because of scatter of data there is occasionally an overlap of the conductance values when the root-mean-square roughness is chosen as a parameter. An explanation of the significance of roughness as expressed in terms of the root-mean-square value was given in reference 1. The reasoning is not affected by the introduction of the pressure parameter.

As might be expected, conductance values for matched specimens of the same material but of different roughnesses are intermediate between those for each of the two roughnesses identically matched. The conductance of an interface formed between 75S-T6 aluminum specimens of 10- and 120-microinch roughness, respectively, is shown in figure 2(f) and the comparison of the above specimen pair and those of identical roughnesses is made in figure 4 for the 200° F and 400° F mean-temperature levels.

Matching of stainless steel with 75S-T6 aluminum gave conductance values which did not lie between those for the same materials in identical pairs, as may be seen by comparing figure 8(b) with figures 2(b) and 2(d). Furthermore, conductance values for the dissimilar pair are greatly different for different directions of heat flow, and there is a reversal of a number of previously established trends. This apparently anomalous behavior is analyzed in the section entitled "Discussion."

Effect of Pressure

Since the interface pressure is the most important of all the parameters influencing the interface conductance, most of the curves were plotted with the conductance and pressure as coordinates. Figures 2(a) to 2(f) show a representative set of conductance-versus-pressure relationships for four sets of 75S-T6 aluminum-alloy specimens and for two sets of stainless-steel specimens with various surface roughnesses. Two test runs were made for each of the four pressures on each curve. Because of the limited number of experimental points the curves as drawn are not as precisely located as they would be if a mean in a band of scatter could have been determined. These curves are adequate, nonetheless, for indication of trends as follows:

(a) The interface conductance increases with pressure. This rise is appreciable in the low pressure range (between 0 and approximately 100 psi) but levels off in the higher pressure range.

(b) The increase of conductance for a given pressure increment is far more pronounced for the soft material (75S-T6 aluminum alloy) than it is for the hard material (stainless steel).

(c) For a given pressure increment the percentage increase of conductance is about the same for all mean interface temperatures. For 75S-T6 aluminum specimens this percentage increase is higher for rougher surfaces, but it is approximately the same for stainless-steel specimens of any roughness.

(d) For a given pressure increment and interface temperature the absolute increase of conductance is higher for smoother surfaces.

(e) For stainless steel, the absolute increase of conductance with pressure seems to be independent of the mean interface temperature, but for 75S-T6 aluminum this increase is approximately twice as much at the 400° F interface temperature as it is at the 200° F interface temperature.

The above trends are reconcilable with the concept that the interface pressure causes microscopic deformations in the interface matching configuration which is further aggravated by the loss of strength of the material at elevated temperatures, especially in the case of the 75S-T6 alloy. These observations will be amplified in the section entitled "Discussion."

Effect of Mean Interface Temperature

The fact that conductance rises with the mean interface temperature level at low interface pressure was established in reference 1. In the present investigation it was found that the percentage rise is of about the same order of magnitude at higher pressure levels as at the low pressure level. As shown in figures 5(a), 5(b), and 5(e), for 75S-T6 aluminum-alloy specimens, an increase in mean interface temperature from 200° F to 400° F causes an increase in conductance of 35 to 110 percent of the low-temperature value (with the rougher specimens showing the greater percentage increase). For stainless-steel specimens, as may be seen in figures 5(c) and 5(d), this percentage increase is smaller, that is, from 15 to 35 percent.

Effect of Temperature Drop

The complete body of available data indicates a tendency for conductance values to increase with the temperature drop Δt when the mean interface temperature and the pressure are held constant. Despite a few examples indicating an opposite trend, or no change at all, the tendency to increase is clearly dominant in the statistical sense. The conductance may be as much as 25 percent higher on account of higher values of Δt (due, in turn, to higher heat flow) in the general case but is never more than 10 percent lower when an opposite trend is indicated.

Effect of Sandwich Material

The effect of brass-foil and asbestos-sheet sandwich material on the conductance was investigated and the results are shown in figures 6 and 7.

As may be seen in figure 6(b), when brass shim 0.001-inch thick was used between rough (100-microinch root-mean-square) stainless-steel interfaces it had little effect on conductance at low pressure but increased the conductance by as much as 50 percent at the highest pressure applied.

A brass shim used between rough 75S-T6 aluminum interfaces again had little effect at low pressure but lowered the interface conductance about 30 percent at the high pressure as in figure 6(a). This difference in the effect of the brass shim on the two different materials is explained in the section entitled "Discussion."

Figure 7, when compared with figure 2(e), shows that the effect of asbestos sheet was to lower the interface conductance for stainless-steel interfaces, at all pressure levels, by about 80 percent.

Time as a Factor in Conductance

An increase of conductance with time was detected during extended runs with 75S-T6 specimens. The entire heating history of each specimen was carefully recorded during testing. Often the specimens were kept at constant temperature for as long as 6 to 8 hours while the load was varied or previous tests were repeated. It was discovered that the interface conductance had a definite tendency to creep higher during these day-long heating periods. Therefore, a time-dependent physical property of the metal (and, consequently, of the interface joint) is also involved in the interface conductance. However, this change was not a permanent one since the initial results were closely reproducible after about 6 hours, during which time the metal was allowed to cool to room temperature; that is, there was no indication that the higher conductance had been retained upon reestablishment of the same conditions.

Effect of Test Reassembly and Interface Matching

As seen in figure 10 it was found that different assemblies of the heating apparatus, without disturbing the interface under investigation, resulted in a scatter of conductance values not exceeding 15 percent. Part of this scatter may be due to instrumentation differences and part due to the time effect discussed above. In any case, test reassembly as such is of doubtful importance, as shown by examples in figure 11. It can be seen in figure 11(a) that conductance can be reproduced within 15 percent even when both a new heating assembly and new interface assembly are made. Results not less consistent can likewise be obtained by testing entirely new specimen pairs of the same roughness as seen in figure 11(b). It is to be realized, of course, that in both instances the separate effects of a new test assembly and interface configuration could have either amplified or canceled one another in determining the reproducibility of any previous conductance value.

In figure 11(c) the results of two tests run with two different pairs of specimens of the same roughness are presented. The large difference between the two tests, observed especially at high pressure, is ascribed to an exceptionally good matching in one of the two tests, not normally attainable in machining by ordinary means. A flatness of 0.0002 inch was maintained in each specimen, but apparently it was possible, without any special care, to machine and match at least one specimen pair to such near perfection that conductances five to six times as high as in the normal case could be attained. The extrapolated temperature drop across such an interface was in the order of 1° F for pressures of over 300 psi.

DISCUSSION

The mechanism of heat transfer across surfaces in contact is exceedingly complex. The great number of interrelated factors make it difficult, if not impossible, to establish a clear-cut cause-and-effect relationship experimentally. From the point of view of obtaining results useful in actual design, only limited success has been attained, since the conductance values measured cannot be precisely duplicated without duplicating the experimental conditions. However, from a design standpoint the data collected do indicate the order of magnitude and range of the conductance values, as well as the trends for their variation.

The trends found by experimentation are more or less expected. That the heat transfer should improve with smoother surface and higher pressure is certainly predictable; that the conductance is not greatly affected by the heat flow or temperature drop is compatible with the concept that cause and effect usually exhibit a certain linear relationship in a small range (i.e., an Ohm's law analogy to heat transfer holds approximately); and that conductance should rise with temperature level might conceivably be reasoned from the increase in the conductivity of the air at higher temperature and by the radiation laws alone. The importance of the results obtained therefore lies in something else, namely, in the extent of reproducibility and consistency. In the present investigation the consistency attained emphasizes the importance of the matching configuration of the interface and indicates a greater complexity of this configuration than previously assumed.

Other investigators of the problem have inquired as to the percentage of heat transferred across the surfaces in contact and to the amount of surface which is in metal-to-metal contact. In the opinion of the authors of the present report, these problems are unanswerable as well as unimportant, not because of the lack of definite results but because of the lack of definition of the concept of surface in "actual" contact. A moment's reflection will reveal that on a microscopic scale there exists no sharp demarcation between contact and separation; and, even if such demarcation could be conceived, as long as the air between the surfaces is a conductor the transition between finite resistance and zero resistance at any place on the interface must be continuous and gradual. Instead of islands of contact and seas of separation the interface should be visualized as a region varying in thickness from the order of atomic spacing to that of a few ten-thousandths of an inch. In this region air molecules of finite size move about randomly under thermal agitation. Such a configuration is capable of changes in an infinite number of ways; some are reflected by a change of conductance and others are not. It is to be expected that the more intimately the two surfaces are in contact the more a small change in the matching configuration will be reflected by a net change of conductance. This accounts for the fact that pressure has a more pronounced effect, as evidenced by the absolute rise of conductance, on smoother surfaces than on rougher surfaces, and that the amount of scattering increases with increasing pressure and decreasing roughness.

The fact that a substantial change in conductance can be brought about without outwardly disturbing the surface matching, as in figure 10, indicates that the so-called separation between the surfaces in contact is of a much smaller order than commonly believed. For specimens with well-prepared flat and smooth surfaces there probably exists a large portion of the total interface area where the separation is of the order of the mean free path of air molecules, that is, a few microinches. A new concept of air film existing between such surfaces may be necessary to explain such striking behavior as seen in test 16 of figure 11(c). Here the two specimens with a surface roughness of 10 microinches root mean square formed a contact joint whose conductance value rose so high that the extrapolated temperature drop Δt at the interface fell to 1° F or less at the highest pressures used. This high interface conductance persisted even after the same specimens were reassembled with a different orientation. It must be pointed out, however, that such near-perfect matching was in a sense only an accident, observed only with one particular pair of specimens. But the fact that such an accident does happen indicates the great sensitivity of conductance value toward minute changes in the matching configuration when the separation is generally small. Fortunately, from a practical point of view, the large fluctuation in the interface conductance occurs only when its value is high, and in such instances the thermal resistance offered by the discontinuity can be neglected.

Of all the factors which contribute to the change in interface matching configuration the factor of interface pressure is perhaps the most important. It produces deformations in the boundary surfaces both elastically and plastically. At low pressure (from 0 to perhaps 100 psi) its effect is especially large. As the pressure increases, the matching becomes more intimate; additional pressure produces increasingly less deformation so that the increase of conductance value tends to level off in the high pressure range. Thus the effect of pressure is more pronounced at low pressure, not because of the difference in over-all deformation of the specimens but because of the local deformation of the so-called "peaks." Similarly, it is noted that the effect of pressure is more pronounced in softer materials than in harder materials. The latter observation may be substantiated by noting the opposite effects upon the conductance value produced by a 0.001-inch brass shim sandwiched between 75S-T6 aluminum and between stainless-steel specimens. There the effect of pressure seems to be governed by the hardness of the surface and sandwich material rather than by the over-all deformation of surfaces. Under any circumstance the plastic deformation produced by the interface pressure upon the surfaces themselves must be highly localized since no measurable change could be detected either in the roughness or in the flatness after the specimens had been subjected to the highest interface pressure applied, but the effect of the scattered localized changes upon the over-all matching configuration may be quite pronounced.

The elastic and plastic deformations caused by the pressure and resulting in a change of interface conductance are undoubtedly influenced by the temperature level of the interface. The large amount of rise, with temperature, in the conductance of interfaces between aluminum-alloy specimens under high interface pressure cannot be attributed solely to changes in air-film conductivity and in the amount of radiation.

It is improbable that the strength of the stainless steel was sufficiently affected by the temperature in the range of the tests to influence the interface conductance. However, it is well known that aluminum alloys behave uniquely when loaded at elevated temperatures. Specifically, the modulus of elasticity of the 75S-T6 alloy, as shown in reference 2, drops approximately 15 percent and both the ultimate tensile stress and tensile yield stress drop as much as 50 percent in the temperature range of the tests, with both effects being accelerated as the temperature increases. It is difficult, of course, to separate the effects of pressure and temperature on the interface configuration, when such is the case. It is believed, however, that the data plotted in figures 5(a), 5(b), and 5(e) point to loss of strength as a mechanism which has just as much, if not more, importance in the rise of conductance with interface temperature as the air-film conductivity and radiation.

The fact that the loss-of-strength effect is negligible in the stainless steel is apparent from figures 5(c) and 5(d); here the tendency shown by the constant-pressure curves is not much altered by either the pressure or the interface temperature.

Once a given test assembly had been subjected to the maximum load at room temperature, subsequent loading cycles at elevated temperatures seemed to cause deformations that were for the most part immediately recoverable in stainless-steel specimens but time-dependent in 2S-O aluminum and 75S-T6 aluminum-alloy specimens. (No data are presented in this report for 2S-O aluminum since the material is of no practical significance. However, tests were performed with 2S-O to check metallurgical effects as compared with 75S-T6.) This time-dependency, partly responsible for the scatter in figures 2(a), 2(b), 2(c), and 2(f), can be ascribed to phenomena involving creep, relaxation, and other metallurgical changes, both physical and chemical. At the temperature levels encountered such phenomena are much more important, as far as the changes in matching configuration are concerned, for 2S-O and 75S-T6 aluminum specimens than for stainless-steel specimens. Hence, for a given assembly, experimental points can be reproduced without much difficulty for the latter. The fluctuation of conductance values associated with the time factor alone was about of the same order for 2S-O aluminum as for 75S-T6 aluminum-alloy specimens even though metallurgical changes such as precipitation and recrystallization are not likely in the 2S-O. Possibly the low yield strength of the 2S-O had the same over-all effect on conductance variations as the metallurgical changes in the 75S-T6 alloy.

Another important factor determining the value of and contributing to the changes in interface conductance is the warping of the bounding surfaces. Because of the temperature gradient in the specimens, both axial and radial, a certain amount of warping is unavoidable. If this warping produces a poorer matching, either at the interface under investigation or at the contact planes with the heating and cooling elements, the resulting nonuniformity in the heat flow produces additional warping which may aggravate or improve the over-all matching pattern. Because of these uncertainties, the effect of warping is difficult to assess.

The series of tests conducted with an assembly of dissimilar materials gave results which are rather difficult to explain adequately. The first arrangement of this type consisted of a 75S-T6 aluminum-alloy specimen in contact with stainless steel, with heat flowing from the aluminum alloy to the steel. This was followed by a second set of tests, without outwardly disturbing the interface assembly, where the specimen pair was inverted so that the heat now flowed from the stainless steel to the 75S-T6 aluminum specimen. It was found that the same interface presented greatly different thermal resistances for the two different directions of heat flow, with the first arrangement giving conductance values several times higher than the second, as may be seen in figure 9. When the heat flowed from the 75S-T6 aluminum to the stainless steel, the conductance values fell roughly between those of 75S-T6 specimen pairs and stainless-steel specimen pairs of comparable roughness. In contrast, the conductance values not only were much lower in the second arrangement, but were even smaller than those displayed by the combination of stainless steel to stainless steel.

In the case of heat flow from 75S-T6 aluminum to stainless steel it was further found that no definite trends with respect to temperature level were discernible, as seen in figure 8(a), such as those observed in identical pairs. In the reversed case, as may be seen in figure 8(b), the trends were definite but reversed in comparison with those found in all other tests. Most important is the decrease of interface conductance with increasing temperature level. (The thermocouples did not have a common ground so any thermal voltage which might have been set up at the interface or between the specimens and thermocouple wire could not affect the reading of the potentiometers.)

This puzzling phenomenon may be partially explained by warping of the specimens. It is known that, aside from the temperature gradient, warping can also be caused at high temperature by the relief of room-temperature residual stresses in an unannealed specimen. It is suspected that even a small amount of warping is of considerable importance from the viewpoint that minute changes in the matching configuration could be critical and that such warping did occur at the elevated temperatures of the tests, especially when the situation was aggravated by the effects of radial and axial temperature gradients.

The mean temperature of the top specimen in contact with the heating element must obviously be higher than the mean interface temperature; conversely, the bottom specimen in contact with the cooling element is always at a lower temperature than the mean interface temperature. Therefore, for a given constant interface temperature level, the mean temperatures of the two individual specimen blocks are always substantially different depending on their position, top or bottom, with respect to the direction of heat flow.

In the explanation of this phenomenon it is theorized that the temperature level partly determines the amount of warping and that warping gets successively more severe as the mean temperature of the specimen blocks increases and the room-temperature residual stresses are gradually relieved. Then, as initial warping of the slightest amount occurs, the contact areas through which heat is transferred tend to shift in location; the original more or less uniform axial heat path is upset and these interrelated changes progress until a balanced condition of local temperatures and over-all warping is reached.

In the course of the tests there were a number of indications pointing to the fact that the warping which resulted in distortion of the interface and abnormal conductance values was mainly due to the stainless-steel specimen in the dissimilar pair, rather than to the 75S-T6 aluminum specimen. When the presence of severe warping was indicated by an unreasonably low conductance value, the readings of several thermocouples placed at different radial and angular positions, but at the same distance from the interface, showed a wide scatter in the stainless-steel specimen. This unmistakably points to a large gradient in the radial direction. It is easy to reason that this large gradient, which is partly due to the poor conductivity of stainless steel, will set up large thermal stresses so that the cause and effect of warping is interlocked.

When the specimen pair was inverted, without disturbing the sealed interface joint, and the heat flowed in the opposite direction, the interface conductance returned to what was believed normal, and, at the same time, the previous scatter in the same thermocouple readings in the stainless-steel specimen dropped to a negligible value. It is to be noted that, in both instances, the scatter was small in the thermocouple readings in the 75S-T6 aluminum specimen.

If it is accepted that the interface conductance decreases with the intensity of warping, which in turn increases with temperature, and, furthermore, if the over-all matching pattern of the combination of stainless steel to aluminum alloy is dominated by the warping of the stainless steel, the trends apparent in figure 8(b) are self-evident and so are the large differences between the two bands of figure 9.

There can be, however, at least one legitimate objection to the above explanation, namely, that the combination of stainless steel to stainless steel showed generally higher conductance values (fig. 2(d)) than the combination of stainless steel to aluminum alloy for one of the two directions of heat flow.

The explanation here must fall back on the previously mentioned fact that the patterns of warping are quite uncertain and, because of unknown heat-flow patterns, unpredictable. It is entirely possible, for instance, that two stainless-steel specimens, obtained from the same lot and prepared by the same machining operations, warp in exactly the same way and approximately to the same curvature under the effect of thermal gradients of the same direction so that the net effect can be a negligible difference in separation of the two specimens with temperature. The warping-versus-thermal-gradient mutual relationship can well be a self-canceling one in this case.

The above-mentioned directionality phenomenon was discussed in some detail because of its general interest, although work beyond the few tests conducted was considered outside the scope of the present investigation. Further investigation of this phenomenon may be of interest.

CONCLUSIONS

The following conclusions have been made upon examination of the experimental results of thermal-conductance measurements:

1. The thermal conductance of the interface joint increases with pressure. This increase is appreciable at low pressures but levels off at higher pressures.

2. For a given pressure increment the percentage increase in conductance is about the same for all mean interface temperatures.

3. The thermal conductance of the interface increases with the mean interface temperature. The percentage of increase is of about the same order of magnitude at high and low pressures.

4. At any pressure level, the thermal conductance of the interface joint generally increases as the root mean square of the surface roughness decreases. However, surface roughness alone is not a dominant parameter in determining thermal conductance of contacts, for over-all flatness has a more important role in determining the configuration of surface matching.

5. There is a tendency for the interface conductance values to increase slightly with the temperature drop Δt when the mean interface temperature and the pressure are held constant.

6. The effect of a 0.001-inch-thick brass foil sandwiched between the surfaces is to increase conductance when the interface material is harder than the brass foil but to decrease conductance when the material is softer. A 0.01-inch-thick asbestos sheet lowers the conductance between stainless-steel surfaces by as much as 80 percent.

7. When subject to repeated heating-and-loading cycles the materials investigated reveal a pronounced but varied loss and recovery of strength,

which causes corresponding changes in thermal conductance of the contact by changing the contact configuration. These changes make it difficult to duplicate exactly a particular pattern of joint matching or interface conductance.

8. Test reassembly and new interface matching give reproducibility of conductance values comparable with that in the experimental scatter of an undisturbed assembly.

9. In general, interfaces formed between rough specimens give more consistent data than those between smooth specimens.

10. Interface conductance has a definite tendency to increase slowly during long heating periods while all experimental conditions are being kept constant. Therefore, a time-dependent physical property of the metal must also be involved in the interface conductance. However, the time effect is only a temporary one and the changes are mostly recoverable after cooling.

11. Because of thermal stresses caused by temperature gradients and uneven heat flow a certain amount of warping of the specimens occurs at the interface. Furthermore, unannealed specimens may experience a relief of the room-temperature residual stresses at elevated temperature which could cause additional warping. Such warping may influence the conductance value far more pronouncedly than either roughness or initial flatness.

12. For extremely smooth and flat surfaces in contact the conductance values are highly sensitive to minute changes in the matching configuration and may vary widely.

13. The results reported herein can be used quantitatively in actual engineering analysis provided that most of the idealized experimental conditions are closely duplicated in an actual design. Otherwise, they serve to indicate qualitatively the relationship between the amount of heat transfer and the various pertinent factors in an actual structural joint.

Syracuse University,
Syracuse, N. Y., February 1, 1954.

REFERENCES

1. Barzelay, Martin E., Tong, Kin Nee, and Holloway, George: Thermal Conductance of Contacts in Aircraft Joints. NACA TN 3167, 1954.

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TABLE I

TEST SCHEDULE AND DESCRIPTION OF SPECIMENS

Test	Specimen	Specimen material (a)	Sandwich material	Surface roughness, microin. rms	Notes
1	50, 51	St. st. to st. st.	None	100-100	
2	15, 16	75S-T6 to 75S-T6	------do------	10-10	
3	15, 16	--------do--------	------do------	10-10	Same assembly as test 2
4	9, 10	--------do--------	------do------	65-65	
5	1, 2	--------do--------	------do------	120-120	
6	15, 16	--------do--------	------do------	10-10	Same assembly as test 3
7	9, 10	--------do--------	------do------	65-65	Same assembly as test 4
8	15, 16	--------do--------	------do------	10-10	Same assembly as test 6
9	50, 51	St. st. to st. st.	------do------	100-100	New assembly following test 1
10	50, 51	--------do--------	Brass shim	100-100	
11	50, 51	--------do--------	Asbestos sheet	100-100	
12	48, 49	--------do--------	None	30-30	
13	9, 10	75S-T6 to 75S-T6	------do------	65-65	New assembly following test 7
14	1, 2	--------do--------	------do------	120-120	New assembly following test 5
15	15, 1	--------do--------	------do------	10-120	
16	17, 18	--------do--------	------do------	10-10	
17	7, 8	--------do--------	------do------	65-65	
18	17, 18	--------do--------	------do------	10-10	Same assembly as test 16
19	3, 4	--------do--------	------do------	120-120	
20	17, 18	--------do--------	------do------	10-10	New assembly following test 18
21	49, 9	St. st. to 75S-T6	------do------	30-65	
22	49, 9	--------do--------	------do------	30-65	New assembly following test 21
23	3, 4	75S-T6 to 75S-T6	Brass shim	120-120	
24	9, 49	75S-T6 to st. st.	None	65-30	Same assembly as test 22 but specimen pair inverted
25	48, 10	St. st. to 75S-T6	------do------	30-65	
26	10, 48	75S-T6 to st. st.	------do------	65-30	Same assembly as test 25 but specimen pair inverted

[a]St. st., stainless steel; 75S-T6, 75S-T6 aluminum alloy.

TABLE II

TEST RESULTS

(a) Test 1.

p (nominal), psi	Δt, °F	Q, Btu/(sq ft)(hr)	h, Btu/(sq ft)(hr)(°F)
$t_m' = 200°$ F			
5	11.2	7,450	670
90	11.1	8,000	720
240	12.0	7,460	620
425	11.4	7,950	700
5	18.0	11,200	620
90	16.9	10,900	640
240	16.3	11,400	700
425	15.6	11,600	740
5	18.5	9,950	540
90	17.8	10,100	570
240	14.8	10,800	730
425	14.1	11,200	790
$t_m' = 300°$ F			
5	23.3	12,800	550
90	21.1	13,700	650
240	19.3	14,000	730
425	17.8	14,600	820
5	22.5	13,300	590
90	20.7	13,900	670
240	19.2	14,300	740
425	18.0	14,200	790
5	25.3	16,300	640
90	24.9	18,000	720
240	22.8	17,600	770
425	20.6	19,100	930
5	25.9	17,200	660
90	23.6	17,600	750
240	21.6	17,700	820
425	21.0	18,900	900
$t_m' = 400°$ F			
5	29.1	20,100	690
90	26.4	20,600	780
240	24.7	21,100	850
425	23.6	21,000	890
5	28.6	19,900	700
90	26.1	21,200	810
240	24.8	20,900	840
425	23.1	20,900	900
5	33.4	24,100	720
90	30.3	25,200	830
240	28.8	28,100	980
425	26.4	27,800	1,050
5	33.4	24,200	720
90	30.9	26,600	860
240	29.0	26,700	920
425	27.1	27,500	1,000

(b) Test 2.

p (nominal), psi	Δt, °F	Q, Btu/(sq ft)(hr)	h, Btu/(sq ft)(hr`(°F)
$t_m' = 200°$ F			
5	17.6	14,500	820
90	6.61	14,600	2,200
240	5.18	14,800	2,850
425	3.61	14,800	4,100
5	13.5	12,900	960
90	6.13	13,700	2,250
240	4.34	14,700	3,400
425	3.40	14,100	4,150
5	8.12	11,800	1,450
90	5.60	13,100	2,350
240	4.54	14,100	3,100
425	3.98	13,600	3,400
$t_m' = 300°$ F			
5	25.1	21,700	860
90	9.68	24,100	2,500
240	6.78	24,600	3,650
425	4.83	26,400	5,450
5	25.6	22,100	860
90	9.14	25,200	2,750
240	6.23	25,100	4,050
425	4.40	25,700	5,850
5	15.3	21,600	1,400
90	8.87	23,500	2,650
240	6.44	25,400	3,950
425	2.92	25,700	8,800
$t_m' = 400°$ F			
5	31.4	32,500	1,050
90	12.6	35,400	2,800
240	7.46	37,600	5,050
425	5.12	38,500	7,500
5	25.4	33,400	1,300
90	13.3	34,900	2,600
240	8.88	36,200	4,100
425	5.40	36,600	6,800
5	20.5	29,000	1,400
90	11.5	33,100	2,900
240	8.17	34,800	4,250
425	5.25	38,500	7,350

(c) Test 3.

p (nominal) psi	Δt, °F	Q, Btu/(sq ft)(hr)	h, Btu/(sq ft)(hr)(°F)
$t_m' = 200°$ F			
5	9.99	12,700	1,250
90	5.26	13,700	2,600
240	4.68	13,700	2,950
425	2.90	13,700	4,700
5	9.40	12,800	1,350
90	5.52	12,700	2,300
240	3.81	13,500	3,550
425	2.98	13,800	4,650
5	15.0	22,600	1,500
90	9.47	25,200	2,650
240	7.46	26,800	3,600
425	4.71	28,300	6,000
5	15.0	23,600	1,550
90	9.48	25,800	2,700
240	7.35	27,500	3,750
425	5.34	28,600	5,350
$t_m' = 300°$ F			
5	16.9	22,000	1,300
90	9.58	23,400	2,450
240	6.92	23,900	3,450
425	4.83	24,500	5,050
5	17.5	22,000	1,250
90	8.99	22,600	2,500
240	6.73	24,100	3,600
425	4.75	24,300	5,100
5	25.9	38,400	1,500
90	17.3	44,600	2,600
240	11.6	49,300	4,250
425	8.14	51,300	6,300
5	27.2	40,300	1,500
90	17.4	46,500	2,650
240	9.10	49,100	5,400
425	8.58	51,400	6,000
$t_m' = 400°$ F			
5	22.0	33,300	1,500
90	12.1	34,400	2,850
240	8.95	35,400	3,950
425	5.85	35,200	6,000
5	19.9	32,400	1,650
90	12.4	33,700	2,700
240	7.87	35,600	4,500
425	6.35	35,800	5,650
5	36.9	58,200	1,600
90	21.0	68,200	3,250
240	11.5	71,500	6,200
425	8.85	74,300	8,400
5	34.6	58,400	1,700
90	18.0	69,300	3,850
240	10.6	73,400	6,900
425	8.27	78,800	9,550

TABLE II.- Continued

TEST RESULTS

(d) Test 4.

p (nominal), psi	Δt, °F	Q, Btu/(sq ft)(hr)	h, Btu/(sq ft)(hr)(°F)
$t_m' = 200^\circ$ F			
5	19.6	12,500	640
90	11.1	12,800	1,150
240	7.74	13,100	1,700
425	6.34	13,400	2,100
5	16.0	10,500	660
90	10.6	12,200	1,150
240	6.95	13,500	1,950
425	4.70	13,500	2,850
5	22.2	18,200	820
90	15.3	21,300	1,400
240	10.8	23,200	2,150
425	8.56	24,200	2,850
5	22.6	19,000	840
90	17.0	21,500	1,250
240	10.7	21,700	2,050
425	8.79	23,100	2,650
$t_m' = 300^\circ$ F			
5	28.1	20,000	710
90	14.3	22,600	1,600
240	8.70	23,100	2,650
425	6.98	23,600	3,400
5	28.1	20,300	720
90	14.7	21,900	1,500
240	8.81	22,800	2,600
425	6.51	22,800	3,500
5	38.8	31,500	810
90	23.8	35,600	1,500
240	17.8	39,100	2,200
425	14.2	41,100	2,900
5	31.7	25,900	820
90	20.9	31,700	1,500
240	16.2	35,800	2,200
425	13.4	38,100	2,850
$t_m' = 400^\circ$ F			
5	28.5	30,400	1,050
90	13.1	33,300	2,550
240	9.22	34,700	3,750
425	6.83	35,000	5,100
5	30.1	31,500	1,050
90	15.8	33,400	2,100
240	9.96	34,500	3,450
425	7.21	35,100	4,850
5	43.3	40,800	940
90	24.7	49,000	2,000
240	14.1	54,800	3,900
425	11.9	58,100	4,900
5	39.1	37,900	970
90	22.5	47,200	2,100
240	15.4	53,300	3,450
425	11.9	57,000	4,800

(e) Test 5.

p (nominal), psi	Δt, °F	Q, Btu/(sq ft)(hr)	h, Btu/(sq ft)(hr)(°F)
$t_m' = 200^\circ$ F			
5	32.5	13,700	420
90	16.1	15,900	990
240	9.68	15,900	1,650
425	7.74	15,600	2,000
5	26.4	11,300	430
90	12.9	14,200	1,100
240	9.25	14,600	1,600
425	6.63	15,000	2,250
5	40.6	14,000	340
90	22.4	20,000	890
240	15.6	21,700	1,400
425	12.5	22,700	1,800
5	38.6	15,400	400
90	21.5	19,200	890
240	15.1	20,900	1,400
425	11.4	22,000	1,950
$t_m' = 300^\circ$ F			
5	44.0	21,400	490
90	16.6	26,000	1,550
240	9.79	26,200	2,700
425	8.48	26,600	3,150
5	39.5	20,500	520
90	17.1	24,800	1,450
240	10.3	25,900	2,500
425	8.26	26,500	3,200
5	49.4	31,700	640
90	23.7	39,000	1,650
240	15.0	42,600	2,850
425	11.9	44,300	3,700
5	47.6	29,300	620
90	22.6	38,000	1,700
240	14.4	42,200	2,950
425	11.5	44,500	3,850
$t_m' = 400^\circ$ F			
5	47.4	31,400	660
90	14.7	37,100	2,500
240	9.81	41,200	4,200
425	6.45	40,200	6,250
5	44.9	32,700	730
90	15.1	37,200	2,450
240	9.24	39,400	4,250
425	7.75	39,700	5,100
5	75.5	44,700	590
90	21.7	58,200	2,700
240	14.3	62,700	4,400
425	12.0	65,900	5,500
5	51.6	41,400	800
90	20.6	55,300	2,700
240	14.0	61,100	4,350
425	12.0	64,200	5,350

(f) Test 6.

p (nominal), psi	Δt, °F	Q, Btu/(sq ft)(hr)	h, Btu/(sq ft)(hr)(°F)
$t_m' = 200^\circ$ F			
5	10.2	17,100	1,700
90	7.14	22,500	3,150
240	4.92	25,200	5,100
425	3.97	25,800	6,500
$t_m' = 300^\circ$ F			
5	13.5	23,800	1,750
90	7.36	26,700	3,650
240	4.28	27,100	6,350
425	3.56	27,800	7,800
$t_m' = 400^\circ$ F			
5	17.5	34,500	1,950
90	8.59	37,500	4,350
240	5.42	39,300	7,250
425	4.00	39,300	9,850

(g) Test 7.

p (nominal), psi	Δt, °F	Q, Btu/(sq ft)(hr)	h, Btu/(sq ft)(hr)(°F)
$t_m' = 200^\circ$ F			
5	18.7	11,800	630
90	12.4	14,500	1,150
240	8.96	15,700	1,750
425	5.96	16,100	2,700
$t_m' = 300^\circ$ F			
5	43.9	32,600	740
90	27.7	41,000	1,500
240	18.8	45,600	2,450
425	15.8	47,800	3,050

TABLE II.- Continued

TEST RESULTS

(h) Test 8.

p (nominal), psi	Δt, °F	Q, Btu/(sq ft)(hr)	h, Btu/(sq ft)(hr)(°F)
$t_m' = 200^\circ$ F			
5	10.4	13,000	1,250
90	5.45	13,400	2,450
240	3.18	14,700	4,600
425	3.21	14,300	4,450
5	8.94	12,500	1,400
90	4.77	13,700	2,850
240	3.10	14,400	4,650
425	3.04	14,200	4,650
5	13.9	22,300	1,600
90	7.90	24,800	3,150
240	6.32	26,200	4,150
425	5.40	27,400	5,050
5	14.1	22,900	1,600
90	8.03	24,700	3,100
240	5.94	26,500	4,450
425	4.34	27,300	6,300
$t_m' = 300^\circ$ F			
5	14.9	22,800	1,550
90	7.71	24,800	3,200
240	4.81	24,900	5,200
425	4.33	25,500	5,900
5	13.7	23,600	1,700
90	7.15	24,600	3,450
240	5.04	24,600	4,900
425	4.73	24,800	5,250
5	22.3	38,800	1,750
90	12.8	42,700	3,350
240	8.43	45,100	5,350
425	7.00	47,700	6,800
5	22.6	39,600	1,750
90	11.6	42,800	3,700
240	8.34	44,400	5,300
425	6.93	46,700	6,750
$t_m' = 400^\circ$ F			
5	17.9	33,700	1,900
90	9.40	35,100	3,750
240	6.15	36,700	5,950
425	4.80	37,200	7,750
5	17.2	33,900	1,950
90	8.98	35,800	4,000
240	6.03	36,800	6,100
425	4.44	36,800	8,300
5	30.3	56,100	1,850
90	15.7	61,500	3,900
240	8.92	60,600	6,800
425	7.92	63,100	7,950
5	27.6	54,900	2,000
90	14.7	57,200	3,900
240	9.46	60,000	6,350
425	7.14	61,100	8,550

(i) Test 9.

p (nominal), psi	Δt, °F	Q, Btu/(sq ft)(hr)	h, Btu/(sq ft)(hr)(°F)
$t_m' = 200^\circ$ F			
5	24.3	9,000	370
90	22.1	9,050	410
240	17.7	9,350	530
425	16.1	9,350	580
5	21.4	8,350	390
90	18.1	8,400	460
240	16.2	8,550	530
425	14.8	8,750	590
5	27.9	10,500	380
90	24.6	11,100	450
240	22.9	11,500	500
425	21.5	11,700	540
5	28.1	10,800	380
90	24.7	11,300	460
240	22.8	11,700	510
425	21.3	11,900	560
$t_m' = 300^\circ$ F			
5	31.9	14,100	440
90	27.1	14,300	530
240	24.0	14,800	620
425	21.9	15,100	690
5	31.6	13,800	440
90	26.6	14,800	560
240	24.1	15,000	620
425	22.0	15,400	700
5	42.6	18,300	430
90	37.5	19,100	510
240	34.7	19,800	570
425	31.9	20,200	630
5	42.5	18,200	430
90	37.3	19,100	510
240	34.6	20,000	580
425	31.7	20,200	640
$t_m' = 400^\circ$ F			
5	42.9	20,400	480
90	38.5	21,500	560
240	33.5	22,100	660
425	30.8	22,500	730
5	42.0	20,600	490
90	36.6	21,600	590
240	37.1	23,900	640
425	33.1	24,000	730
5	55.0	26,700	490
90	49.5	27,800	560
240	45.3	29,300	650
425	42.2	29,400	700
5	56.6	26,600	470
90	50.2	28,500	570
240	44.9	29,200	650
425	42.6	29,700	700

(j) Test 10.

p (nominal), psi	Δt, °F	Q, Btu/(sq ft)(hr)	h, Btu/(sq ft)(hr)(°F)
$t_m' = 200^\circ$ F			
5	23.8	9,000	380
90	17.1	9,600	560
240	11.5	9,450	820
425	9.89	9,600	970
5	26.5	10,200	380
90	23.0	11,400	500
240	18.8	12,100	640
425	16.9	12,800	760
$t_m' = 300^\circ$ F			
5	30.3	14,100	470
90	21.7	14,900	690
240	16.6	15,300	920
425	15.4	15,300	990
5	42.5	18,500	440
90	32.6	19,500	600
240	26.6	20,600	770
425	24.4	21,000	860
$t_m' = 400^\circ$ F			
5	41.7	21,400	510
90	30.2	22,400	740
240	25.5	22,800	890
425	23.0	23,100	1,000
5	55.9	27,400	490
90	43.7	28,800	660
240	35.7	30,200	850
425	32.0	30,500	950

TABLE II.- Continued

TEST RESULTS

(k) Test 11.

p (nominal), psi	Δt, °F	Q, Btu/(sq ft)(hr)	h, Btu/(sq ft)(hr)(°F)
$t_m' = 200^\circ$ F			
5	78.5	7,000	89
90	67.0	7,200	110
240	59.7	7,800	130
425	55.6	7,900	140
5	83.6	8,500	100
90	78.8	9,150	120
240	75.1	9,750	130
425	72.8	10,000	140
$t_m' = 300^\circ$ F			
5	118	11,400	97
90	104	12,400	120
240	96.5	12,900	130
425	90.5	13,200	150
5	136	15,100	110
90	126	16,000	130
240	119	16,800	140
425	115	17,300	150
$t_m' = 400^\circ$ F			
5	160	16,400	100
90	141	16,600	120
240	133	20,200	150
425	121	19,800	160
5	191	21,200	110
90	176	23,000	130
240	163	23,900	150
425	156	25,000	160

(l) Test 12.

p (nominal), psi	Δt, °F	Q, Btu/(sq ft)(hr)	h, Btu/(sq ft)(hr)(°F)
$t_m' = 200^\circ$ F			
5	6.95	8,050	1,150
90	5.56	8,250	1,500
240	4.92	8,000	1,650
425	5.18	8,600	1,650
5	6.01	7,350	1,200
90	4.48	7,650	1,700
240	4.25	8,200	1,950
425	4.08	8,100	2,000
5	7.91	10,700	1,350
90	7.23	11,500	1,600
240	6.65	11,700	1,750
425	6.31	12,000	1,900
5	8.13	11,000	1,350
90	7.77	11,600	1,500
240	6.69	11,900	1,800
425	6.28	12,100	1,950
$t_m' = 300^\circ$ F			
5	9.83	13,600	1,400
90	7.76	13,800	1,800
240	7.42	14,400	1,950
425	6.50	14,300	2,200
5	9.18	13,300	1,450
90	8.09	13,800	1,700
240	7.90	14,600	1,850
425	7.94	14,700	1,850
5	12.7	18,700	1,450
90	11.2	19,400	1,750
240	9.95	19,700	2,000
425	9.49	20,000	2,100
5	12.7	18,700	1,450
90	10.1	19,500	1,950
240	9.88	19,800	2,000
425	9.48	19,600	2,050
$t_m' = 400^\circ$ F			
5	12.4	21,200	1,700
90	10.2	22,500	2,200
240	9.67	22,500	2,350
425	9.82	22,700	2,300
5	12.8	20,900	1,650
90	10.6	21,400	2,000
240	9.93	21,500	2,150
425	9.50	22,300	2,350
5	16.9	27,800	1,650
90	15.8	26,800	1,700
240	13.5	28,400	2,100
425	12.6	28,000	2,200

(m) Test 13.

p (nominal), psi	Δt, °F	Q, Btu/(sq ft)(hr)	h, Btu/(sq ft)(hr)(°F)
$t_m' = 200^\circ$ F			
5	18.3	11,400	620
90	11.3	13,500	1,200
240	7.40	14,500	1,950
425	5.29	14,800	2,800
5	16.5	11,300	680
90	10.4	13,100	1,250
240	6.42	14,300	2,250
425	4.95	14,500	2,950
5	27.3	20,700	760
90	18.7	24,600	1,300
240	12.5	28,300	2,250
425	8.98	29,700	3,300
5	27.5	21,300	770
90	18.1	25,700	1,400
240	12.5	28,400	2,250
425	8.85	29,400	3,300
$t_m' = 300^\circ$ F			
5	27.2	20,700	760
90	15.2	23,800	1,550
240	10.1	25,000	2,500
425	7.20	25,700	3,550
5	25.5	20,100	790
90	14.9	23,200	1,550
240	11.1	25,700	2,300
425	6.74	25,700	3,800
5	41.1	36,600	890
90	25.3	43,200	1,700
240	16.9	46,900	2,800
425	12.3	49,800	4,050
5	41.7	38,100	910
90	23.6	43,900	1,850
240	15.9	47,000	2,950
425	11.4	49,800	4,350
$t_m' = 400^\circ$ F			
5	33.6	31,200	930
90	16.2	35,500	2,200
240	9.68	37,200	3,850
425	7.79	37,600	4,850
5	36.9	36,700	990
90	17.5	33,800	1,950
240	10.7	45,000	4,200
425	6.47	42,300	6,550
5	55.8	52,300	940
90	29.1	63,500	2,200
240	18.5	68,600	3,700
425	14.0	70,400	5,050
5	53.8	53,900	1,000
90	27.0	62,000	2,300
240	18.2	67,400	3,700
425	12.8	70,300	5,500

TABLE II.- Continued

TEST RESULTS

(n) Test 14.

p (nominal), psi	Δt, °F	Q, Btu/(sq ft)(hr)	h, Btu/(sq ft)(hr)(°F)
$t_m' = 200°$ F			
5	32.3	9,050	280
90	15.8	12,200	770
240	9.04	13,600	1,500
425	5.16	14,200	2,750
5	32.7	9,600	290
90	15.4	12,300	800
240	8.69	13,300	1,550
425	6.09	13,700	2,250
5	26.3	9,900	380
90	11.3	12,600	1,100
240	7.66	14,300	1,850
425	5.61	15,600	2,800
5	29.5	10,700	360
90	12.1	13,200	1,100
240	7.00	14,900	2,150
425	5.88	16,400	2,800
$t_m' = 300°$ F			
5	49.2	17,500	360
90	15.8	21,400	1,350
240	10.2	23,500	2,300
425	8.65	24,300	2,800
5	46.5	17,100	370
90	16.5	21,700	1,300
240	9.20	23,200	2,500
425	8.68	23,700	2,750
5	47.2	18,600	390
90	15.5	22,800	1,450
240	9.99	25,600	2,550
425	6.97	28,100	4,050
5	48.3	18,800	390
90	15.6	23,400	1,500
240	11.1	25,200	2,250
425	8.17	28,100	3,450
$t_m' = 400°$ F			
5	56.0	27,600	490
90	17.9	32,600	1,800
240	10.1	35,500	3,500
425	7.52	36,300	4,850
5	33.1	17,300	520
90	12.3	22,100	1,800
240	7.43	24,300	3,250
425	5.03	26,200	5,200
5	57.9	30,000	520
90	14.9	35,700	2,400
240	10.0	39,900	4,000
425	8.81	43,300	4,900
5	58.6	30,300	520
90	16.2	36,600	2,250
240	9.52	40,200	4,200
425	8.30	43,200	5,200

(o) Test 15.

p (nominal), psi	Δt, °F	Q, Btu/(sq ft)(hr)	h, Btu/(sq ft)(hr)(°F)
$t_m' = 200°$ F			
5	33.5	12,600	380
90	14.1	15,100	1,050
240	5.98	15,900	2,650
425	4.03	16,200	4,000
5	27.0	12,000	440
90	13.5	14,100	1,050
240	5.88	14,900	2,550
425	4.31	15,300	3,550
5	33.9	15,700	460
90	17.0	21,500	1,250
240	8.85	26,400	3,000
425	8.00	28,400	3,550
5	35.6	17,400	490
90	15.2	22,500	1,500
240	9.41	26,700	2,850
425	6.92	29,000	4,200
$t_m' = 300°$ F			
5	41.7	21,500	520
90	15.3	24,500	1,600
240	8.47	25,500	3,000
425	6.17	26,900	4,350
5	43.9	22,300	510
90	19.3	25,600	1,350
240	7.50	26,700	3,550
425	5.95	27,500	4,600
5	54.5	30,700	560
90	24.7	40,500	1,650
240	12.2	47,100	3,850
425	9.69	49,900	5,150
5	54.2	32,200	590
90	26.2	40,500	1,550
240	12.7	47,100	3,700
425	9.43	50,000	5,300
$t_m' = 400°$ F			
5	49.2	31,900	650
90	15.8	37,900	2,400
240	9.08	40,800	4,500
425	6.62	41,300	6,250
5	46.6	31,300	670
90	16.6	36,900	2,200
240	9.69	39,300	4,050
425	7.32	40,700	5,550
5	65.0	44,100	680
90	28.7	59,100	2,050
240	13.5	66,800	4,950
425	10.1	71,600	7,100
5	66.5	47,200	710
90	28.4	60,200	2,100
240	12.0	68,700	5,750
425	9.16	72,800	7,950

(p) Test 16.

p (nominal), psi	Δt, °F	Q, Btu/(sq ft)(hr)	h, Btu/(sq ft)(hr)(°F)
$t_m' = 200°$ F			
5	11.2	13,400	1,200
90	4.16	14,700	3,550
240	2.46	15,200	6,200
425	1.71	15,300	8,950
5	8.66	13,100	1,500
90	3.63	14,400	3,950
240	1.11	15,200	13,700
425	.71	15,300	21,500
5	16.9	23,200	1,350
90	8.54	26,600	3,100
240	3.71	28,200	7,600
425	2.62	29,400	11,200
5	16.7	23,100	1,400
90	5.78	26,300	4,550
240	2.86	28,300	9,900
425	2.12	29,400	13,900
$t_m' = 300°$ F			
5	15.6	23,000	1,450
90	5.49	25,600	4,650
240	2.19	26,500	12,100
425	1.14	26,700	23,400
5	13.9	22,900	1,650
90	4.48	25,200	5,650
240	2.19	26,500	12,100
425	.95	26,500	27,900
5	25.9	38,500	1,500
90	9.29	44,000	4,750
240	4.04	48,200	11,900
425	2.42	50,100	20,700
5	25.0	40,000	1,600
90	8.80	45,600	5,200
240	4.20	48,200	11,500
425	2.59	50,000	19,300
$t_m' = 400°$ F			
5	17.7	35,900	2,050
90	6.15	38,300	6,250
240	2.02	39,100	19,400
425	1.00	39,700	39,700
5	14.7	34,700	2,350
90	4.94	37,700	7,650
240	1.40	39,300	28,100
425	.86	40,000	46,500
5	26.2	57,800	2,200
90	7.10	63,700	8,950
240	3.49	67,400	19,300
425	2.32	70,400	30,300
5	22.4	57,700	2,600
90	7.05	63,300	9,000
240	3.14	67,000	21,300
425	1.92	70,800	36,900

TABLE II.- Continued

TEST RESULTS

(q) Test 17.

p (nominal), psi	Δt, °F	Q, Btu/(sq ft)(hr)	h, Btu/(sq ft)(hr)(°F)
$t_m' = 200^\circ$ F			
5	20.9	12,900	620
90	11.6	14,500	1,250
240	7.69	15,300	2,000
425	5.91	15,500	2,600
5	20.4	12,700	620
90	12.0	14,300	1,200
240	7.71	15,400	2,000
425	5.75	15,700	2,750
5	30.2	20,600	680
90	18.2	24,200	1,350
240	12.7	28,100	2,200
425	9.30	28,200	3,050
5	30.9	20,800	670
90	16.7	24,500	1,450
240	11.3	26,900	2,400
425	9.47	28,400	3,000
$t_m' = 300^\circ$ F			
5	29.9	21,500	720
90	15.4	24,500	1,600
240	10.1	25,800	2,550
425	7.88	26,700	3,400
5	29.1	21,700	750
90	17.6	23,900	1,350
240	10.5	26,200	2,500
425	7.72	27,100	3,500
5	42.7	33,700	790
90	22.8	40,700	1,800
240	13.3	45,200	3,400
425	10.5	47,700	4,550
5	43.3	35,300	820
90	22.4	41,000	1,850
240	13.6	45,800	3,350
425	11.2	47,600	4,250
$t_m' = 400^\circ$ F			
5	49.4	36,900	750
90	28.5	39,200	1,400
240	11.1	38,600	3,500
425	7.57	37,500	4,950
5	44.2	33,400	760
90	18.2	39,400	2,150
240	9.14	39,500	4,300
425	6.56	39,600	6,050
5	72.0	53,300	740
90	39.1	64,300	1,650
240	16.0	67,800	4,250
425	13.3	71,100	5,350

(r) Test 18.

p (nominal), psi	Δt, °F	Q, Btu/(sq ft)(hr)	h, Btu/(sq ft)(hr)(°F)
$t_m' = 200^\circ$ F			
5	5.11	16,100	3,150
90	2.99	16,900	5,650
240	1.02	16,400	16,100
425	(a)	15,500	------
5	7.04	24,200	3,450
90	5.29	27,000	5,100
240	3.90	28,500	7,300
425	3.55	29,600	8,350
$t_m' = 300^\circ$ F			
5	7.82	26,600	3,400
90	2.92	25,600	8,750
240	(a)	26,800	------
425	1.75	26,700	15,300
5	11.0	39,400	3,600
90	5.24	44,300	8,450
240	1.86	47,300	25,400
425	1.04	49,700	47,800
$t_m' = 400^\circ$ F			
5	10.8	36,700	3,400
90	3.45	38,100	11,000
240	1.44	39,600	27,500
425	(a)	40,200	------
5	20.6	55,700	2,700
90	6.16	65,400	10,600
240	3.18	69,700	21,900
425	2.16	72,200	33,400

[a]Negligible (less than 0.50° F).

(s) Test 19.

p (nominal), psi	Δt, °F	Q, Btu/(sq ft)(hr)	h, Btu/(sq ft)(hr)(°F)
$t_m' = 200^\circ$ F			
5	29.7	10,300	350
90	18.4	13,600	740
240	12.0	15,900	1,350
425	9.90	16,300	1,650
5	28.1	9,850	350
90	14.3	11,300	790
240	10.5	13,100	1,250
425	8.19	14,500	1,750
5	46.5	14,100	300
90	24.2	20,500	850
240	16.7	25,200	1,500
425	12.4	26,900	2,150
5	47.9	15,500	320
90	22.7	20,200	890
240	15.0	24,400	1,650
425	10.6	26,600	2,500
$t_m' = 300^\circ$ F			
5	52.8	19,900	380
90	25.8	23,900	930
240	14.5	25,900	1,800
425	8.68	26,200	3,000
5	46.0	17,700	380
90	23.6	22,300	940
240	15.6	25,100	1,600
425	9.67	27,200	2,800
5	63.6	24,100	380
90	33.9	32,300	950
240	20.3	39,600	1,950
425	16.5	43,800	2,650
5	66.6	25,600	380
90	32.2	33,900	1,050
240	21.5	40,400	1,900
425	15.8	44,600	2,800
$t_m' = 400^\circ$ F			
5	76.3	31,200	410
90	24.0	32,700	1,350
240	14.7	36,000	2,450
425	11.3	38,200	3,400
5	50.0	22,000	440
90	25.9	30,400	1,150
240	15.7	34,600	2,200
425	10.9	37,400	3,450
5	98.6	37,300	380
90	45.1	57,600	1,300
240	28.4	64,900	2,300
425	21.8	70,200	3,200
5	10.7	42,300	400
90	42.8	60,100	1,400
240	26.2	68,000	2,600
425	21.2	69,500	3,300

TABLE II.- Continued

TEST RESULTS

(t) Test 20.

p (nominal), psi	Δt, °F	Q, Btu/(sq ft)(hr)	h, Btu/(sq ft)(hr)(°F)
		$t_m' = 200^\circ$ F	
5	5.55	10,400	1,850
90	2.15	10,600	4,950
240	1.10	11,200	10,200
425	(a)	11,800	------
5	4.75	8,400	1,750
90	2.68	10,100	3,750
240	1.25	10,700	8,550
425	1.39	11,000	7,900
5	5.33	12,300	2,300
90	4.20	15,500	3,700
240	2.59	17,700	6,850
425	2.34	20,200	8,650
5	5.50	11,700	2,150
90	6.31	14,900	2,350
240	3.58	17,900	5,000
425	3.63	19,900	5,500
		$t_m' = 300^\circ$ F	
5	9.38	18,900	2,000
90	5.04	21,300	4,250
240	3.28	22,900	7,000
425	1.24	23,800	19,200
5	7.86	15,000	1,900
90	3.98	18,300	4,600
240	2.34	20,100	8,600
425	1.46	21,700	14,900
5	22.1	40,800	1,850
90	12.9	44,600	3,450
240	7.07	48,700	6,900
425	6.91	50,900	7,350
5	15.5	31,400	2,050
90	10.3	38,200	3,700
240	6.66	42,700	6,400
425	4.80	46,500	9,700
		$t_m' = 400^\circ$ F	
5	19.5	37,300	1,900
90	8.39	38,000	4,550
240	4.40	39,100	8,900
425	1.75	39,800	22,700
5	14.8	33,800	2,300
90	7.41	35,700	4,800
240	3.37	36,900	10,900
425	1.10	36,800	33,500
5	32.6	53,600	1,650
90	15.8	64,300	4,050
240	7.72	68,300	8,850
425	4.04	70,900	17,500
5	29.3	56,300	1,900
90	14.5	65,300	4,500
240	7.89	69,900	8,850
425	4.08	72,900	17,900

[a]Negligible (less than 0.50° F).

(u) Test 21.

p (nominal), psi	Δt, °F	Q, Btu/(sq ft)(hr)	h, Btu/(sq ft)(hr)(°F)
		$t_m' = 200^\circ$ F	
5	27.2	14,500	530
90	22.8	15,100	660
240	18.9	14,900	790
425	18.2	15,100	830
5	19.3	12,000	620
90	21.5	14,200	660
240	18.9	14,800	780
425	16.8	15,100	900
5	36.2	17,700	490
90	41.8	21,600	520
240	40.7	22,900	560
425	42.2	23,300	550
5	39.0	18,600	480
90	40.8	21,000	510
240	42.4	23,200	550
425	42.3	23,500	560
		$t_m' = 300^\circ$ F	
5	47.7	23,200	490
90	46.7	24,500	520
240	42.6	25,200	590
425	36.6	24,800	680
5	34.7	19,000	550
90	39.2	23,600	600
240	38.1	24,100	630
425	36.1	24,600	680
5	69.6	31,200	450
90	81.3	35,700	440
240	84.1	39,400	470
425	84.3	39,700	470
5	71.7	30,600	430
90	81.0	36,000	440
240	85.0	38,300	450
425	85.5	40,100	470
		$t_m' = 400^\circ$ F	
5	78.5	32,700	420
90	73.8	33,400	450
240	71.0	36,300	510
425	64.7	37,000	570
5	63.2	28,300	450
90	63.5	32,000	500
240	66.5	35,000	530
425	62.8	34,800	550
5	107	40,400	380
90	126	48,500	380
240	128	52,100	410
425	131	54,700	420
5	119	42,700	360
90	131	50,000	380
240	137	54,200	400
425	127	54,200	430

(v) Test 22.

p (nominal), psi	Δt, °F	Q, Btu/(sq ft)(hr)	h, Btu/(sq ft)(hr)(°F)
		$t_m' = 200^\circ$ F	
5	25.6	14,400	560
90	22.4	15,000	670
240	17.8	14,100	790
425	16.5	14,900	900
5	43.8	20,000	460
90	47.4	23,900	500
240	44.9	25,200	600
425	43.1	25,900	600
		$t_m' = 300^\circ$ F	
5	48.8	24,100	490
90	45.5	25,400	560
240	40.6	25,000	620
425	37.4	26,200	700
5	60.4	28,400	470
90	75.2	33,200	440
240	83.4	37,700	450
425	80.3	40,300	500
		$t_m' = 400^\circ$ F	
5	72.8	32,600	450
90	63.6	33,000	520
240	61.8	34,300	560
425	56.5	37,400	660
5	85.5	38,300	450
90	93.4	42,500	460
240	98.8	48,300	490
425	99.2	49,700	500

TABLE II.- Concluded

TEST RESULTS

(w) Test 23.

p (nominal), psi	Δt, °F	Q, Btu/(sq ft)(hr)	h, Btu/(sq ft)(hr)(°F)
t_m' = 200° F			
5	33.2	12,000	360
90	23.1	14,400	620
240	16.7	16,500	990
425	12.6	16,800	1,350
5	45.1	15,300	340
90	34.4	22,600	660
240	27.4	26,300	960
425	22.3	28,400	1,250
t_m' = 300° F			
5	55.8	21,300	380
90	32.1	23,900	740
240	22.4	26,900	1,200
425	16.9	26,600	1,550
5	79.4	29,200	370
90	47.0	40,000	850
240	35.8	44,900	1,250
425	28.2	48,100	1,700
t_m' = 400° F			
5	74.7	34,200	460
90	41.5	42,800	1,050
240	23.9	42,600	1,800
425	19.2	44,300	2,300
5	98.8	38,600	390
90	51.5	56,000	1,100
240	35.6	61,400	1,700
425	30.5	64,800	2,100

(x) Test 24.

p (nominal), psi	Δt, °F	Q, Btu/(sq ft)(hr)	h, Btu/(sq ft)(hr)(°F)
t_m' = 200° F			
5	8.78	7,500	850
90	8.90	7,800	880
240	3.75	8,300	2,200
425	2.15	8,350	3,900
5	11.6	11,800	1,000
90	6.36	11,900	1,850
240	5.10	12,200	2,400
425	3.72	12,600	3,400
t_m' = 300° F			
5	16.3	13,600	830
90	9.84	14,100	1,450
240	4.42	14,400	3,250
425	3.15	14,200	4,500
5	24.1	18,100	750
90	13.4	19,900	1,500
240	8.31	20,200	2,450
425	6.24	20,800	3,350
t_m' = 400° F			
5	26.0	19,800	760
90	13.8	21,200	1,550
240	6.51	20,100	3,100
425	4.58	20,900	4,550
5	34.4	25,500	740
90	19.7	26,300	1,350
240	11.5	28,100	2,450
425	7.35	29,100	3,950

(y) Test 25.

p (nominal), psi	Δt, °F	Q, Btu/(sq ft)(hr)	h, Btu/(sq ft)(hr)(°F)
t_m' = 200° F			
5	32.9	12,900	390
90	31.6	14,000	440
240	28.5	14,700	520
425	25.1	15,300	610
5	46.3	15,900	340
90	54.8	20,800	380
240	58.9	23,500	400
425	58.3	25,400	440
t_m' = 400° F			
5	133	40,900	310
90	146	50,000	340
240	130	49,000	380
425	130	51,000	390

(z) Test 26.

p (nominal), psi	Δt, °F	Q, Btu/(sq ft)(hr)	h, Btu/(sq ft)(hr)(°F)
t_m' = 200° F			
5	9.76	9,450	970
90	6.66	9,250	1,400
240	3.26	9,850	3,000
425	1.78	10,100	5,650
5	12.1	11,000	910
90	7.05	12,300	1,750
240	3.76	13,100	3,500
425	1.67	13,400	8,000
t_m' = 400° F			
5	20.6	20,800	1,000
90	17.3	20,800	1,200
240	10.0	22,900	2,300
425	5.51	23,400	4,250
5	28.1	25,500	910
90	22.8	26,400	1,150
240	18.0	27,600	1,550
425	7.33	28,600	3,900

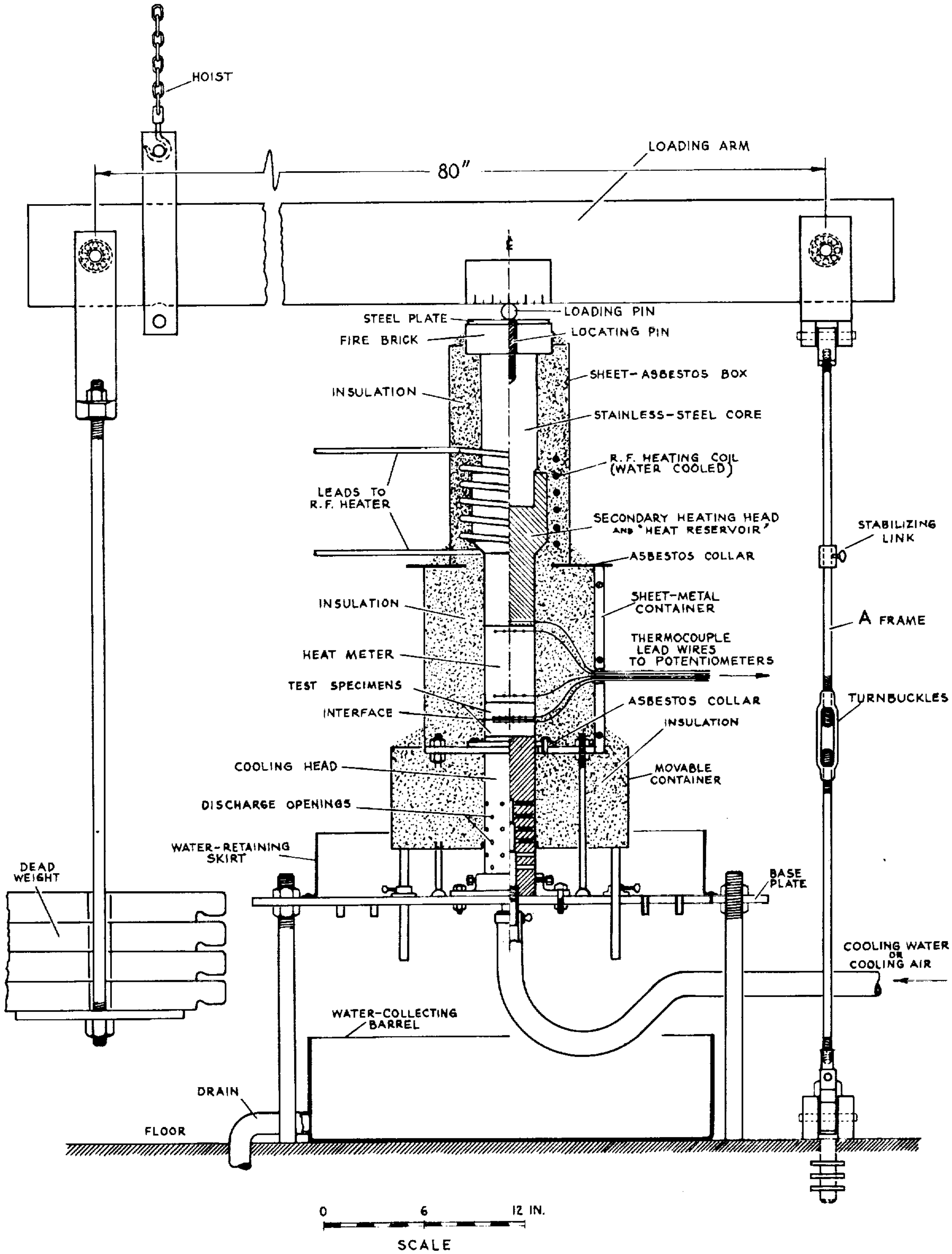
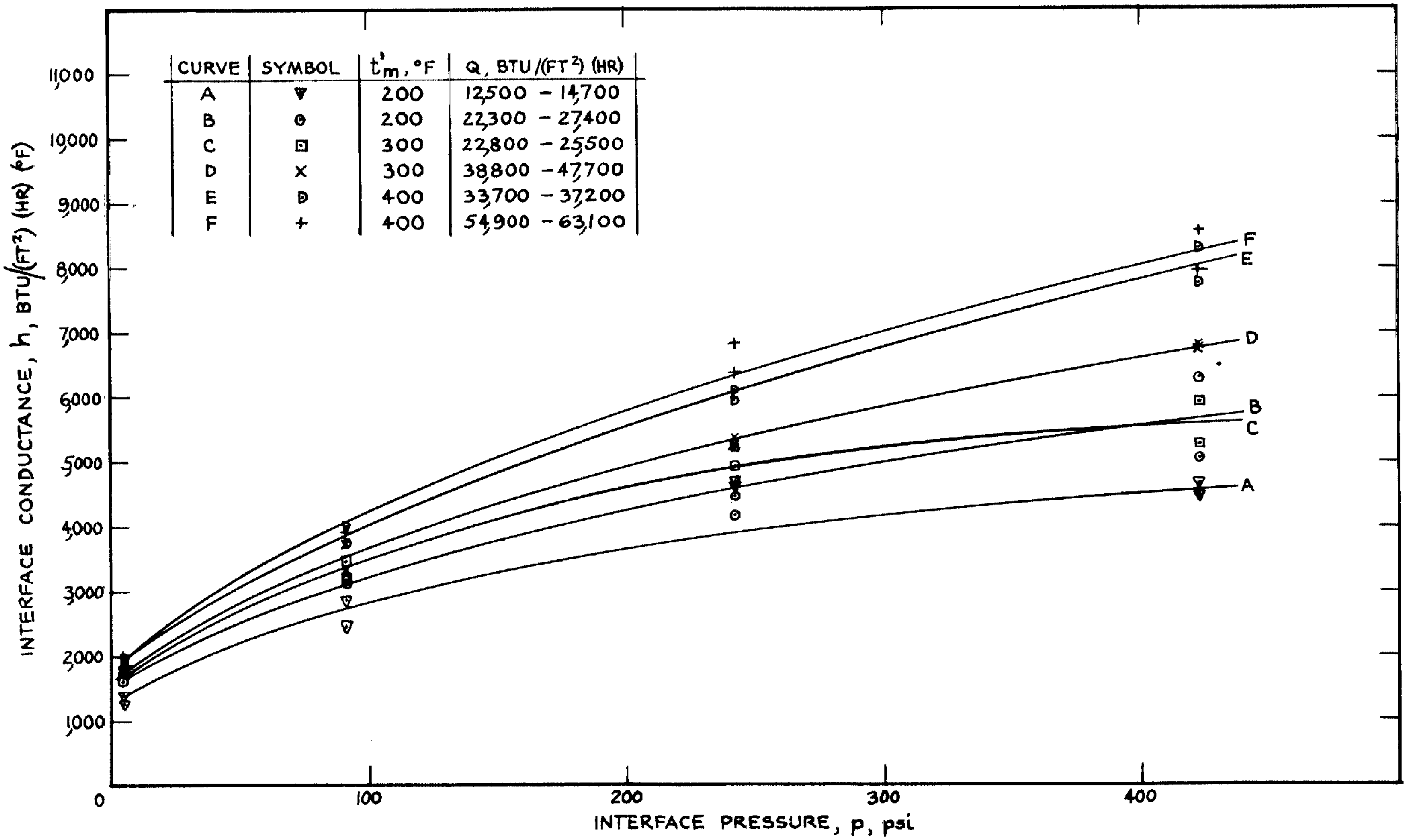
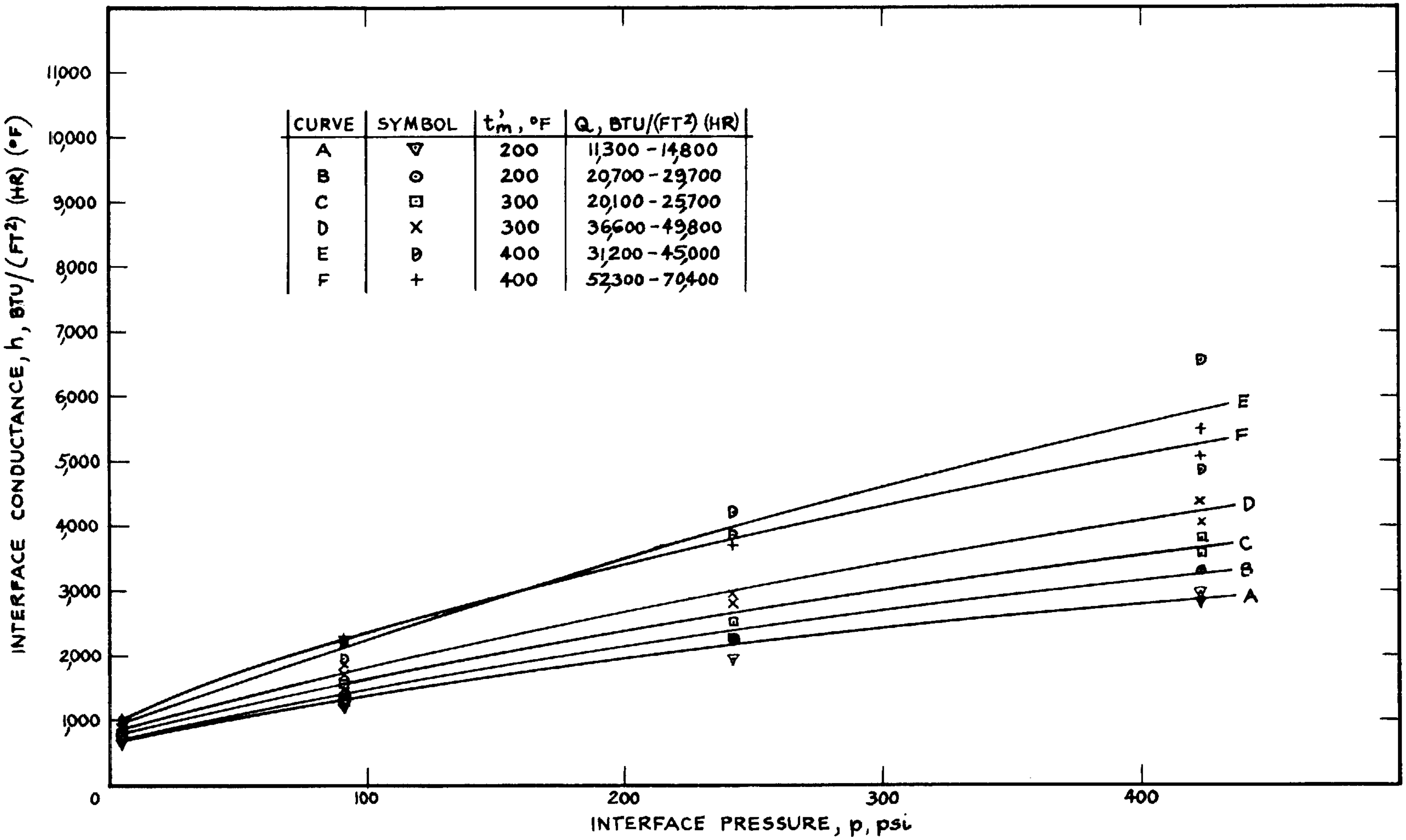


Figure 1.- Assembly drawing of test installation.



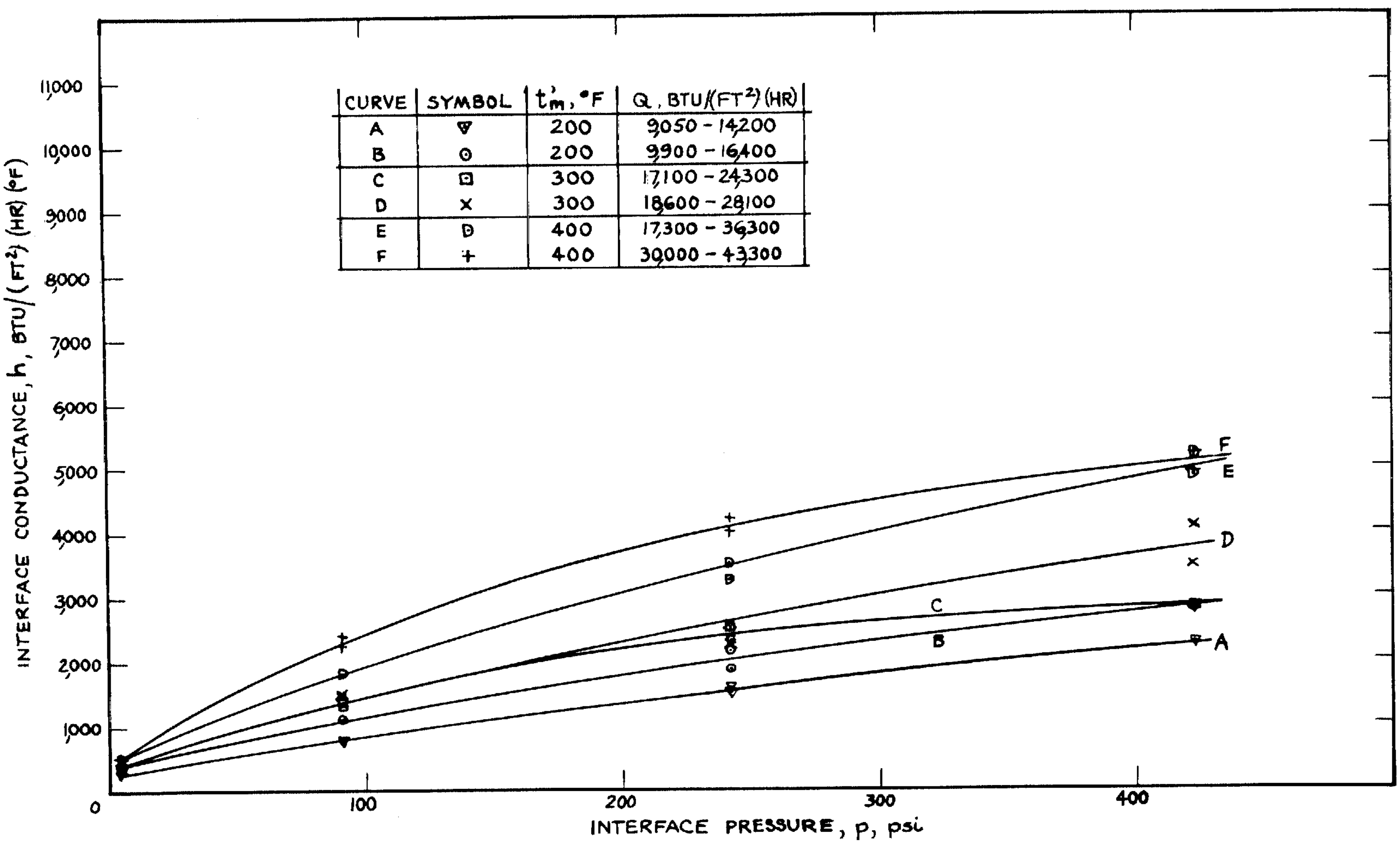
(a) Test 8, specimens 15 and 16; 75S-T6 aluminum-to-aluminum joint; 10-microinch root-mean-square surface roughness.

Figure 2.- Variation of interface conductance with interface pressure.



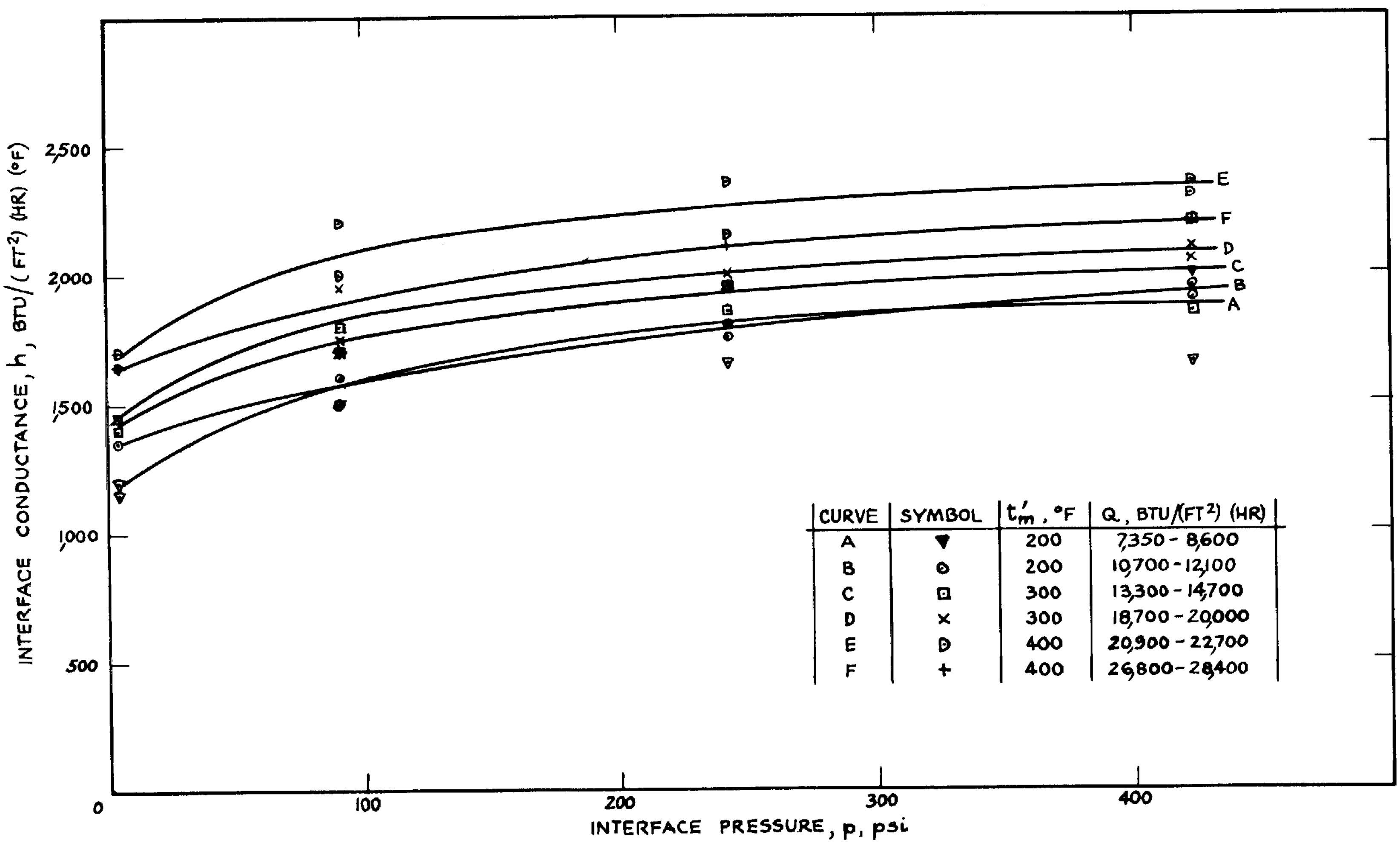
(b) Test 13, specimens 9 and 10; 75S-T6 aluminum-to-aluminum joint; 65-microinch root-mean-square surface roughness.

Figure 2.- Continued.



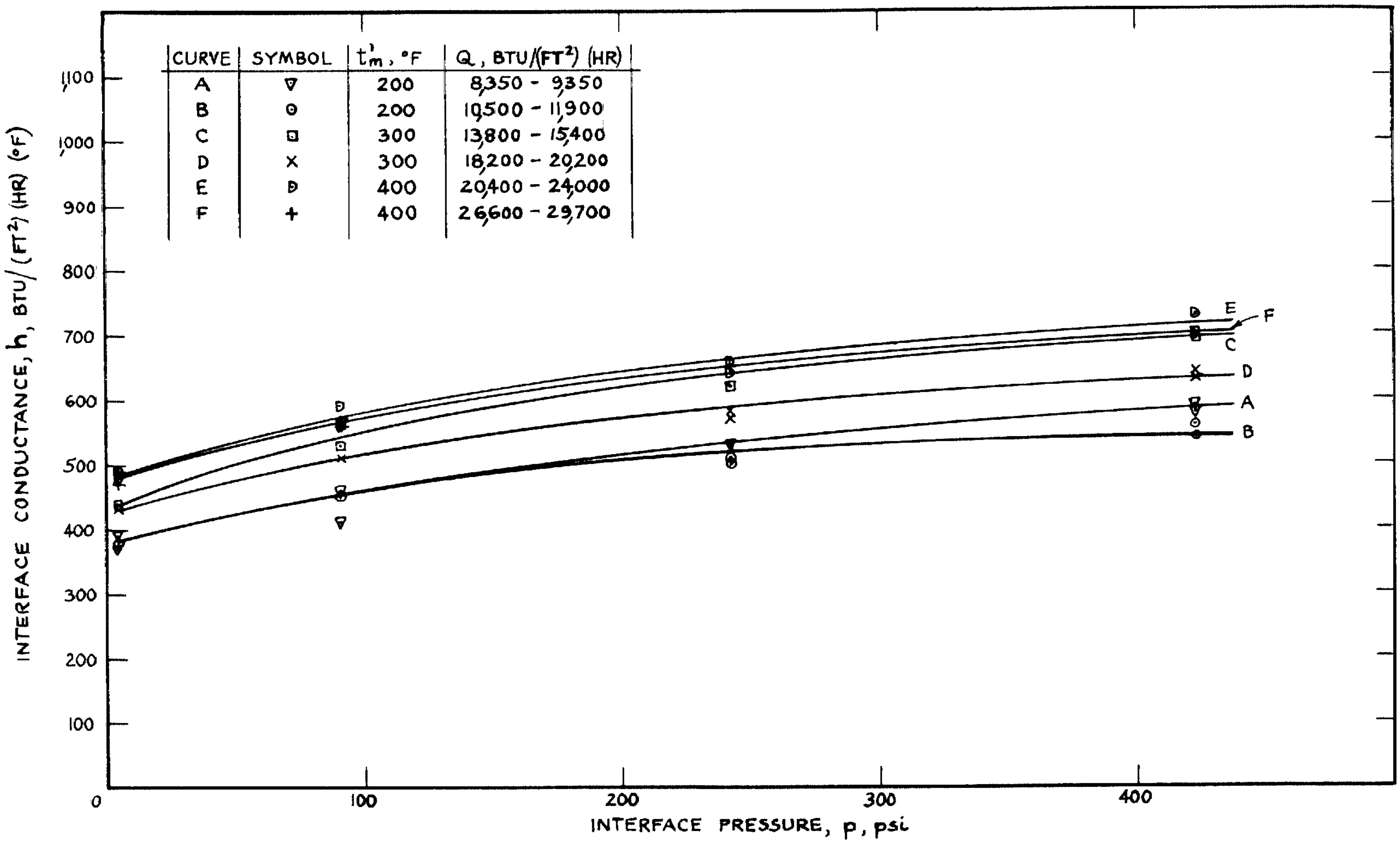
(c) Test 14, specimens 1 and 2; 75S-T6 aluminum-to-aluminum joint; 120-microinch root-mean-square surface roughness.

Figure 2.- Continued.



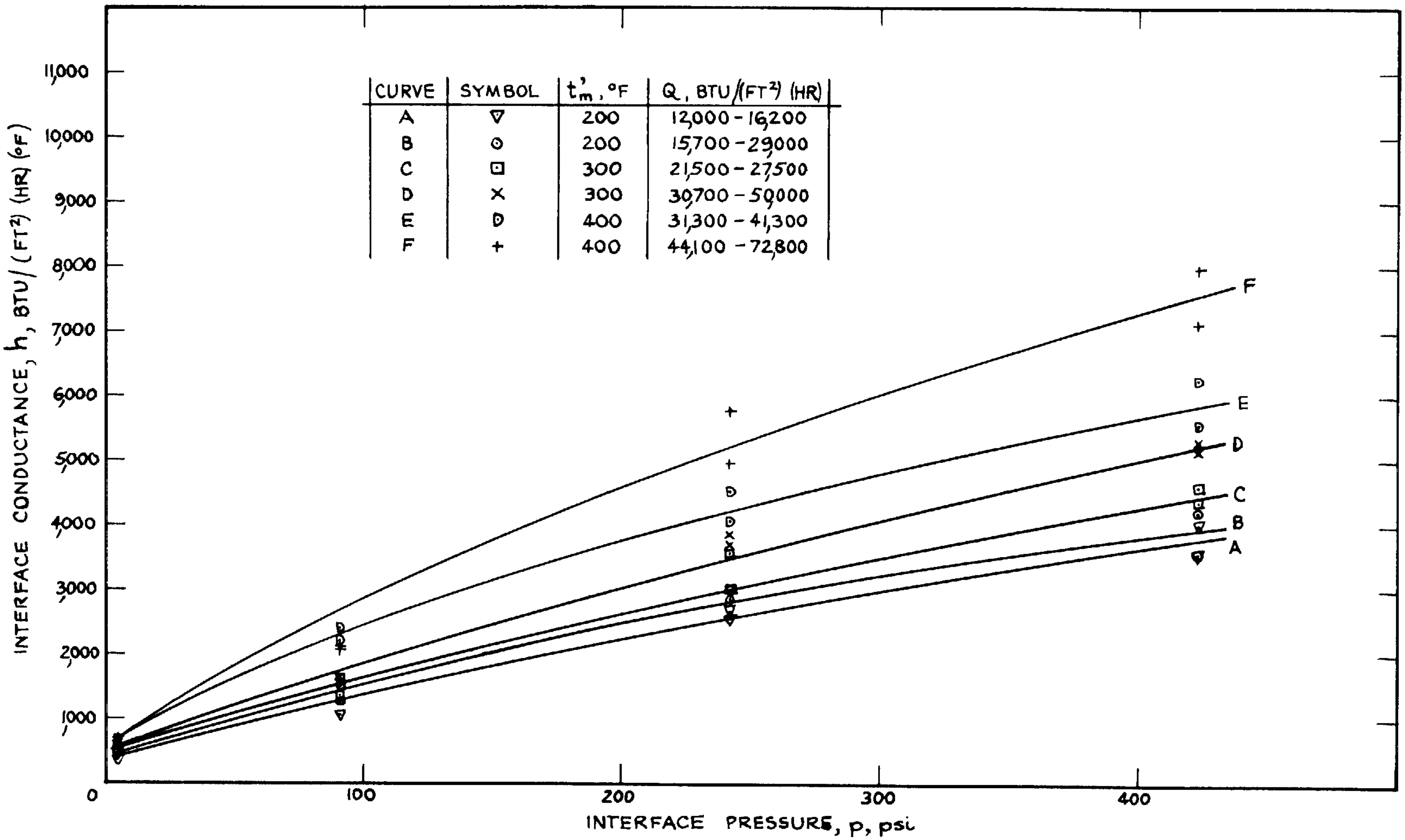
(d) Test 12, specimens 48 and 49; joint of stainless steel to stainless steel; 30-microinch root-mean-square surface roughness.

Figure 2.- Continued.



(e) Test 9, specimens 50 and 51; joint of stainless steel to stainless steel; 100 microinch root-mean-square surface roughness.

Figure 2.- Continued.



(f) Test 15, specimens 15 and 1; 75S-T6 aluminum-to-aluminum joint; 10- and 120-microinch root-mean-square surface roughness.

Figure 2.- Concluded.

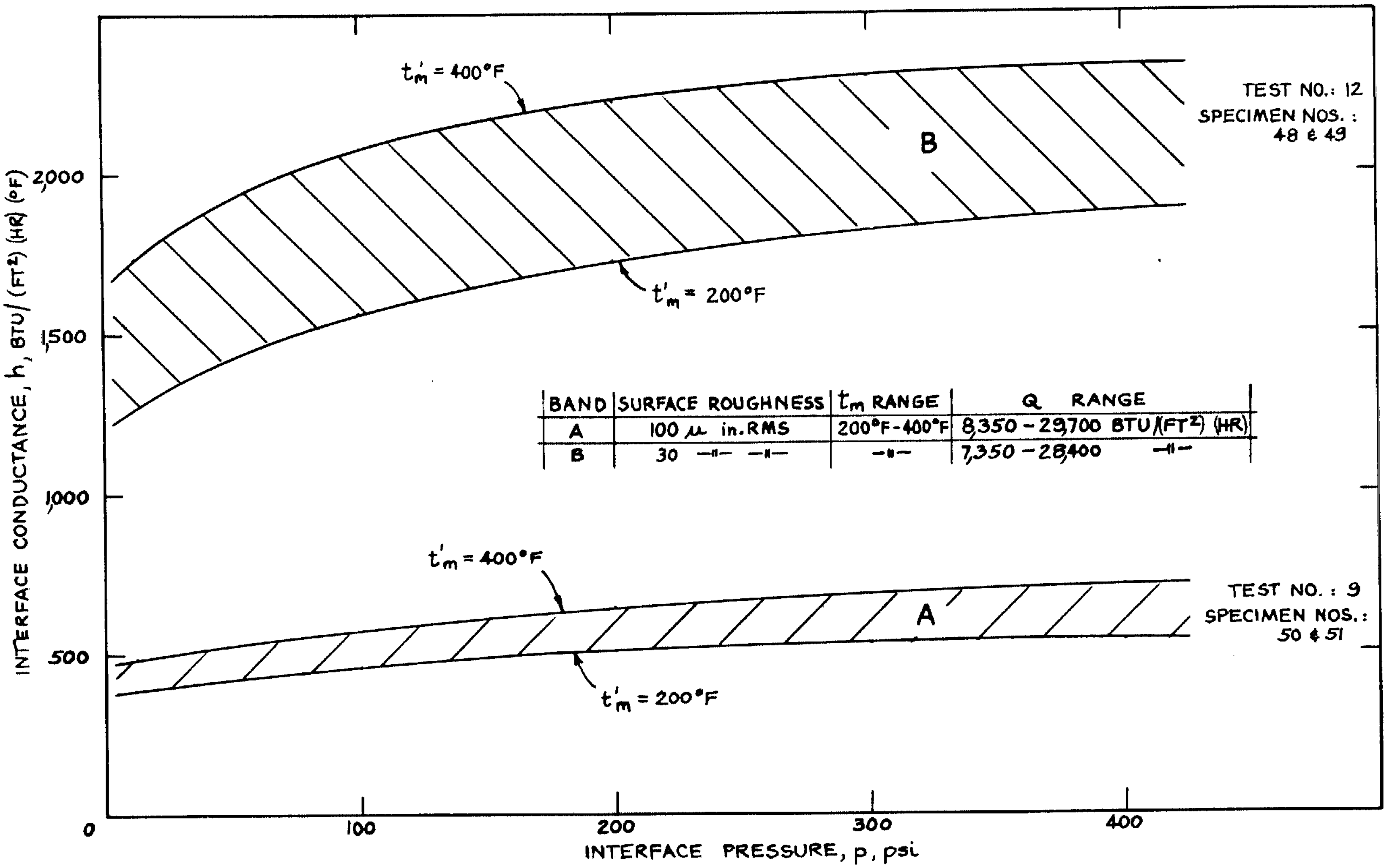


Figure 3.- Comparison of effect of different surface roughnesses of joints of stainless steel to stainless steel on interface conductance.

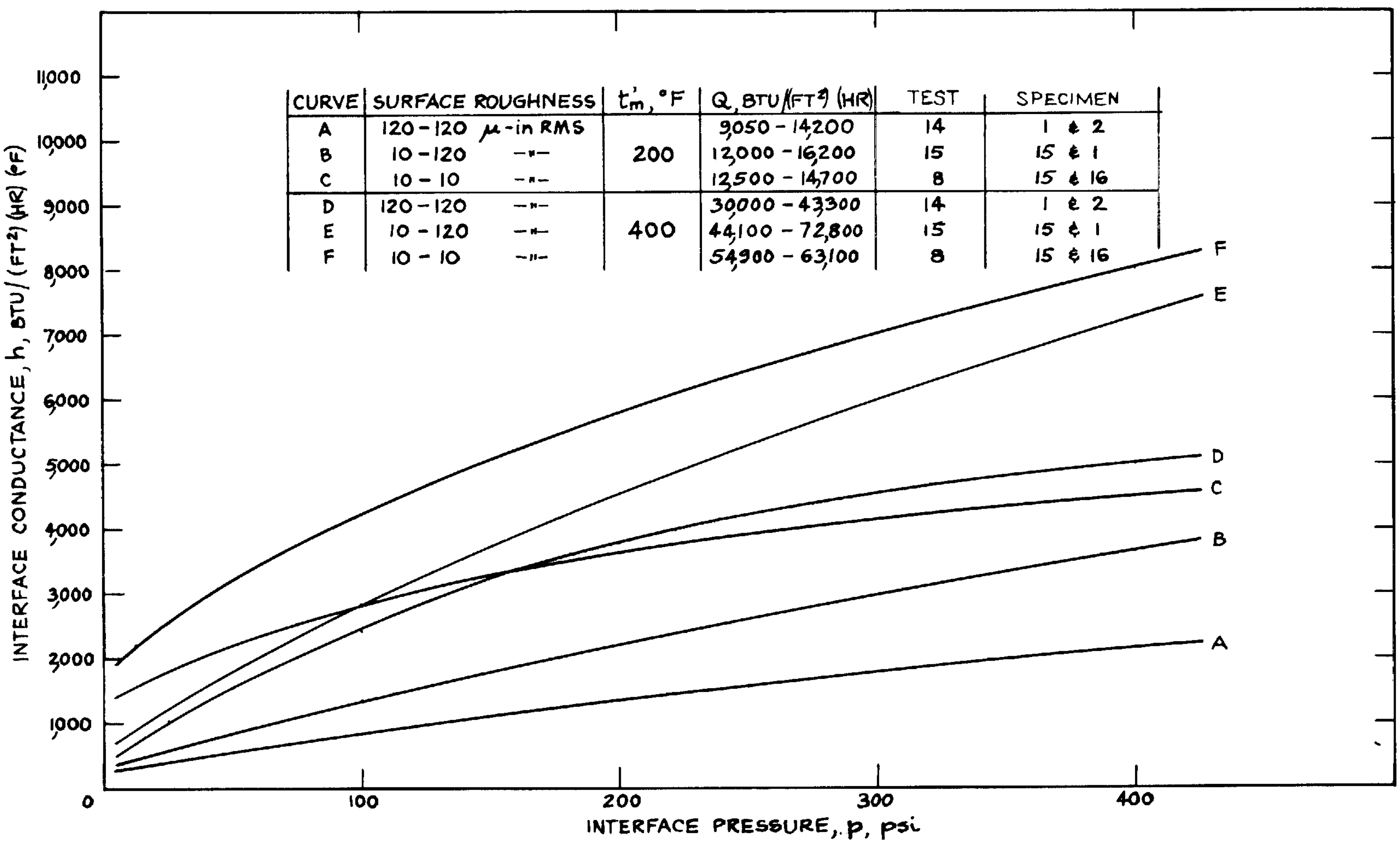
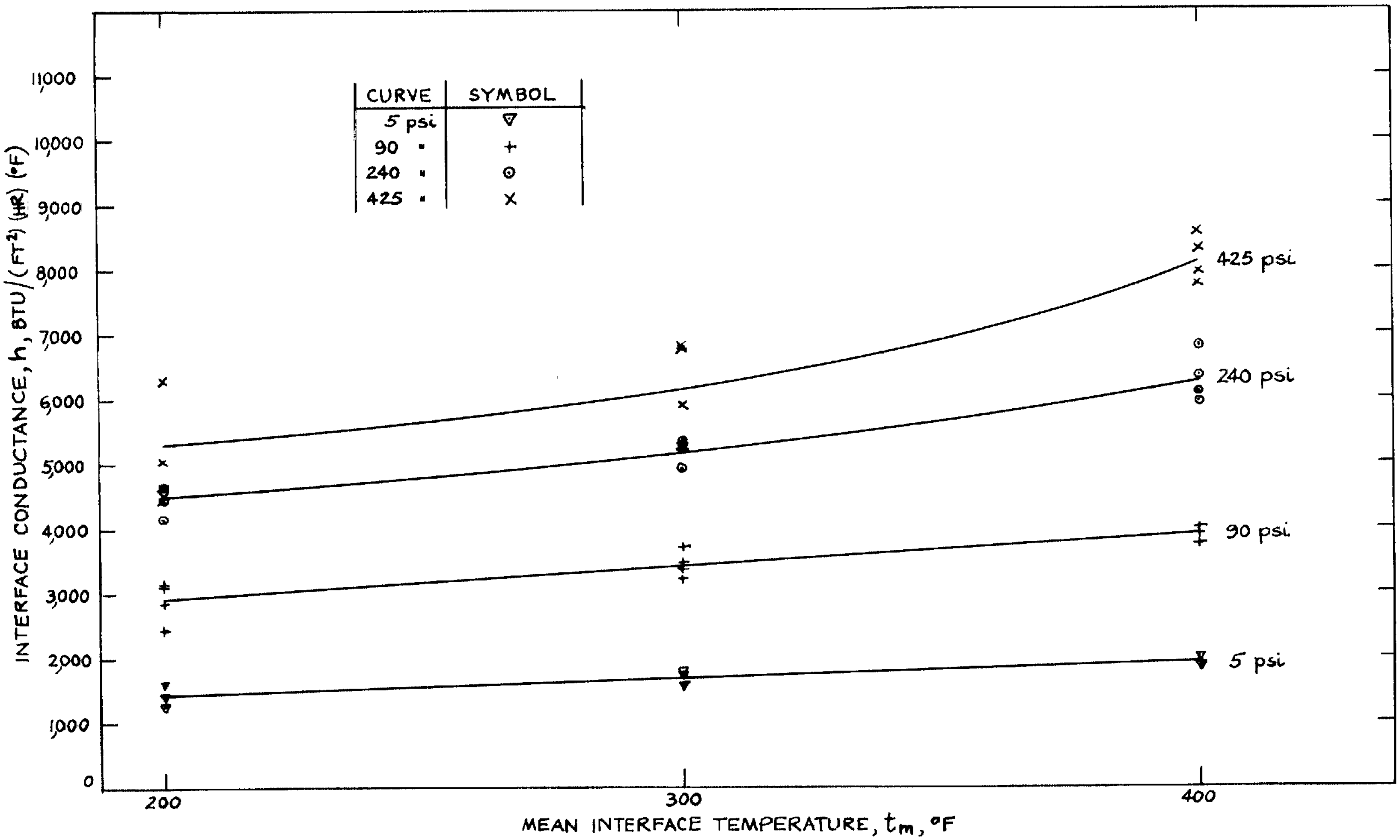
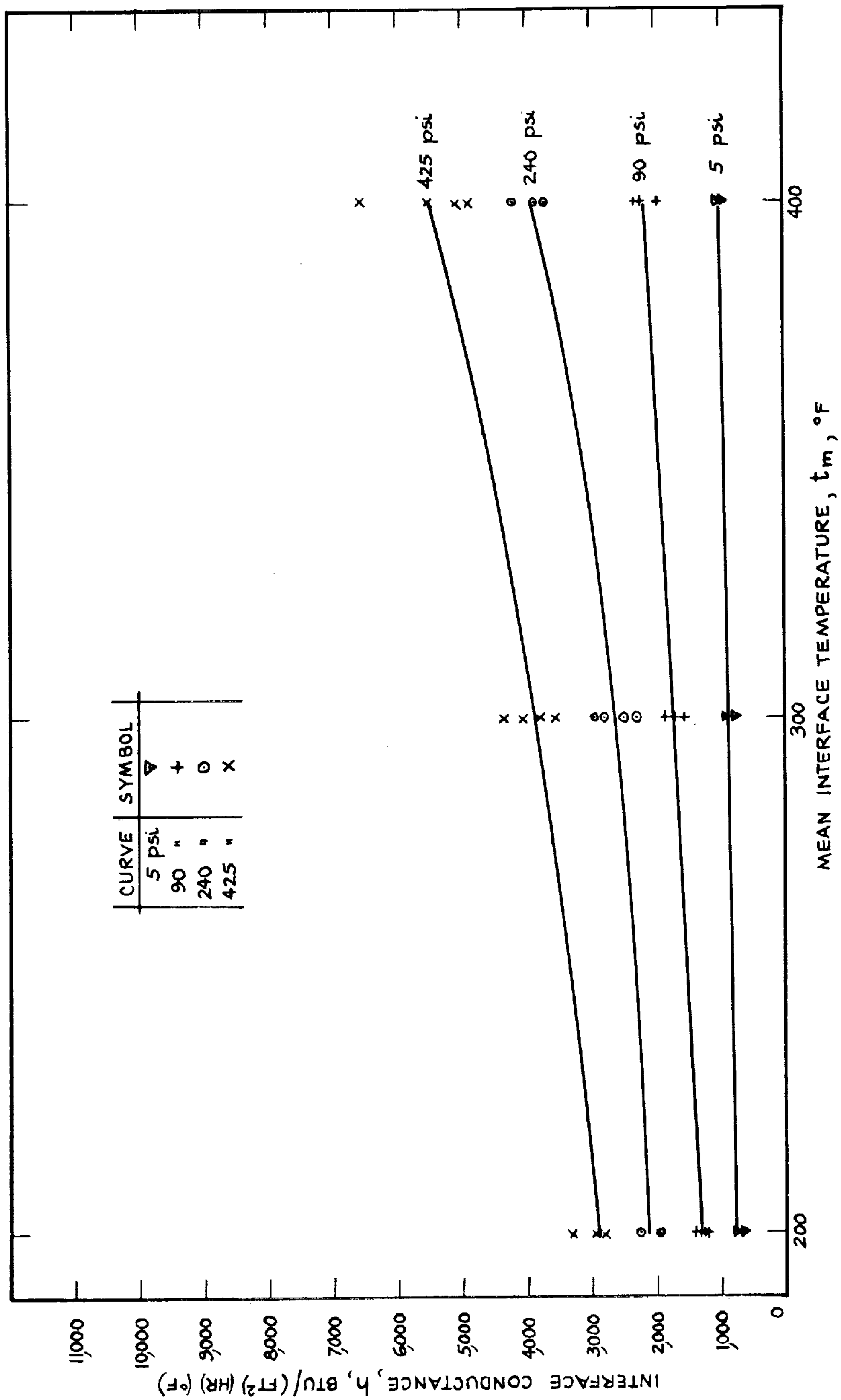


Figure 4.- Comparison of interface conductance values of identical and nonidentical roughness matching at various interface pressures for 75S-T6 aluminum-to-aluminum joints.



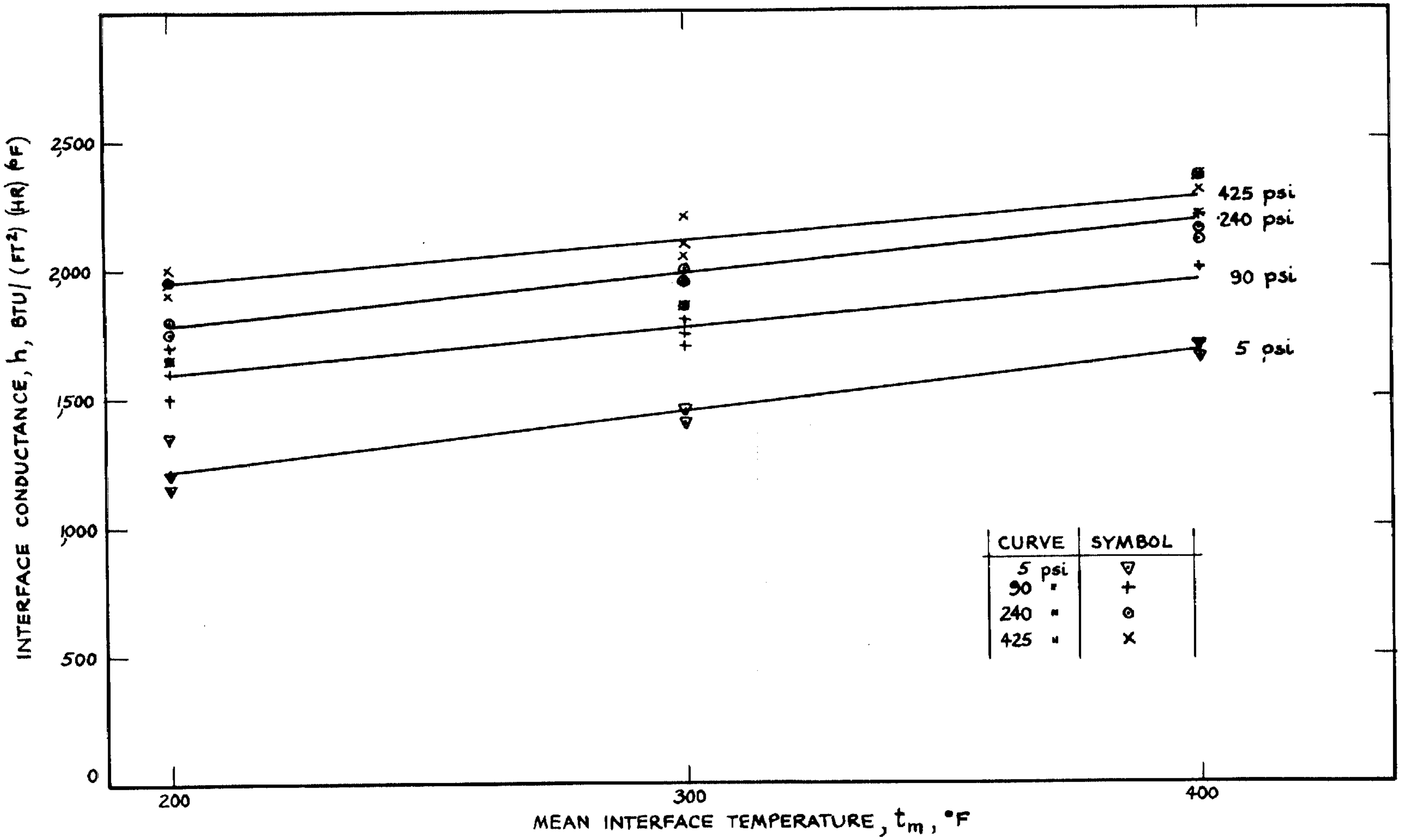
(a) Test 8, specimens 15 and 16; 75S-T6 aluminum-to-aluminum joint; 10-microinch root-mean-square surface roughness.

Figure 5.- Variation of interface conductance with mean interface temperature.



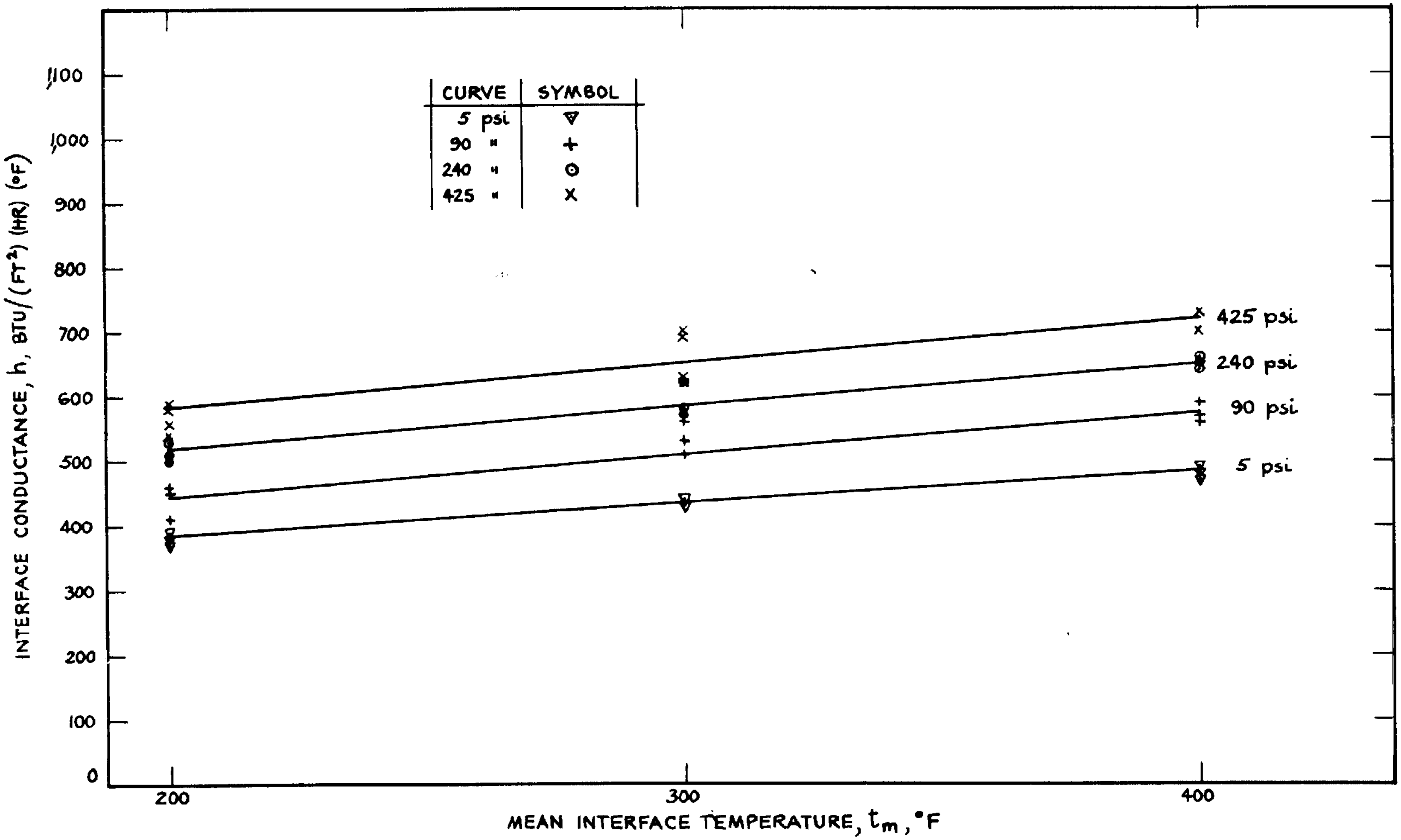
(b) Test 13, specimens 9 and 10; 75S-T6 aluminum-to-aluminum joint; 65-microinch root-mean-square surface roughness.

Figure 5.- Continued.



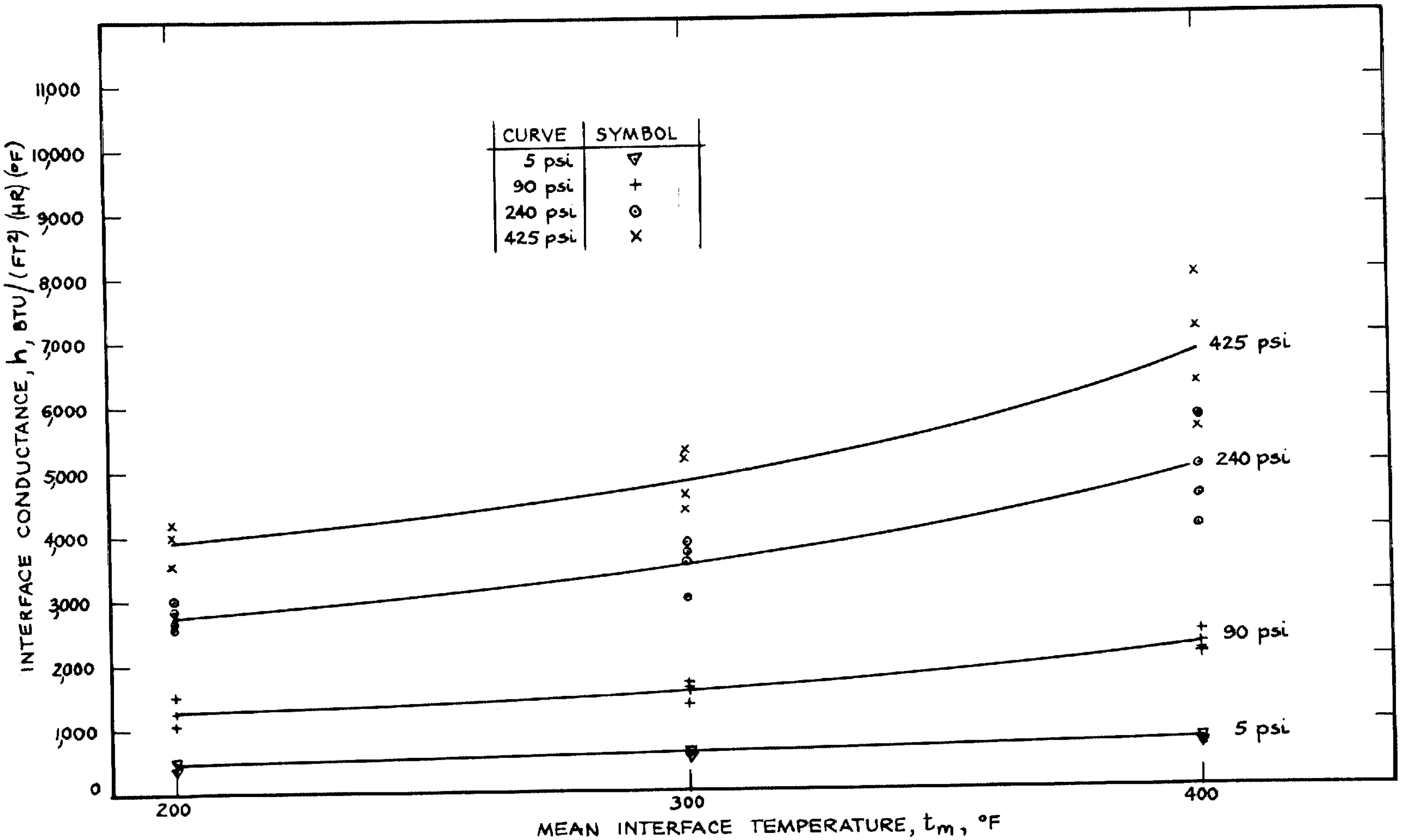
(c) Test 12, specimens 48 and 49; joint of stainless steel to stainless steel; 30-microinch root-mean-square surface roughness.

Figure 5.- Continued.



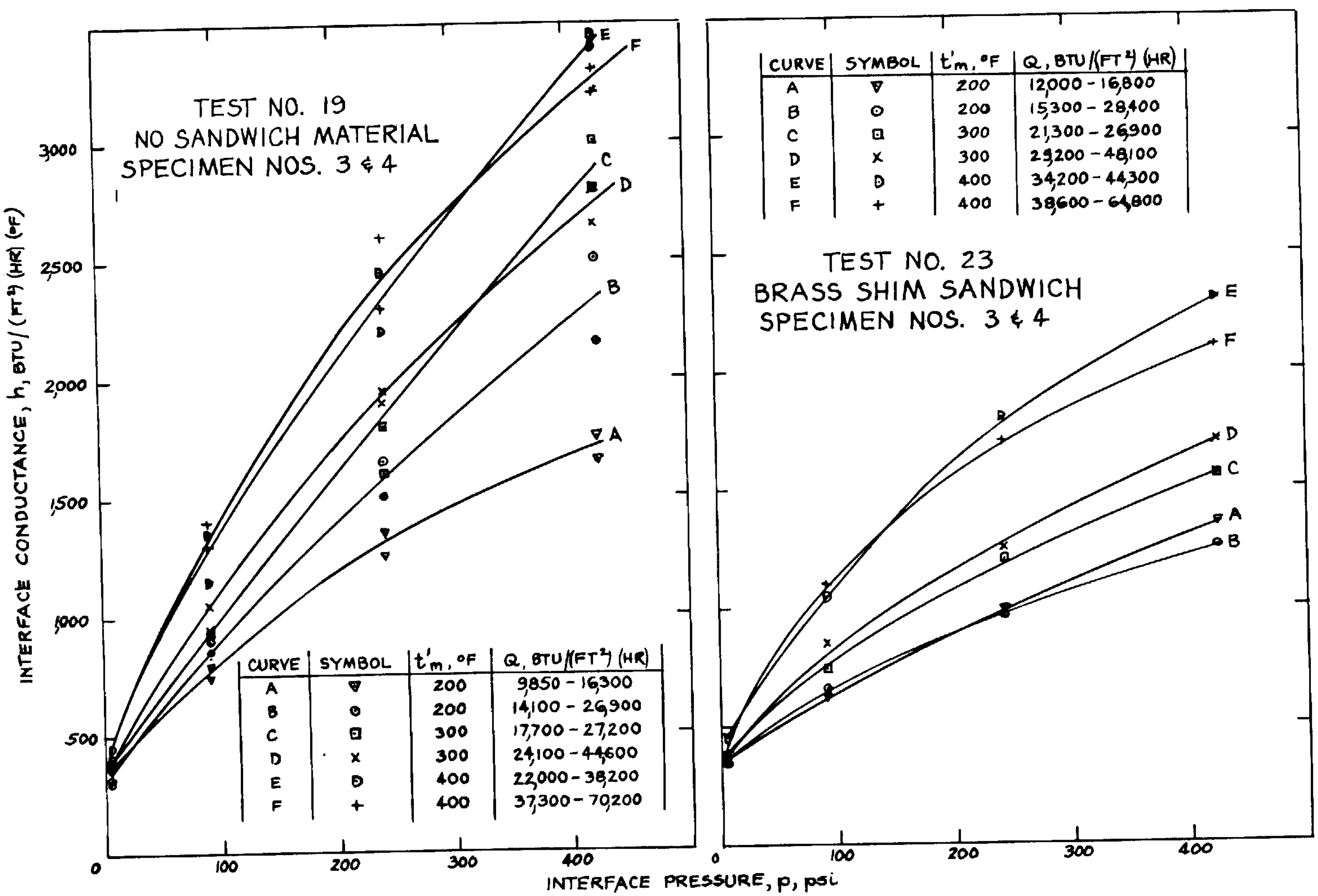
(d) Test 9, specimens 50 and 51; joint of stainless steel to stainless steel; 100-microinch root-mean-square surface roughness.

Figure 5.- Continued.



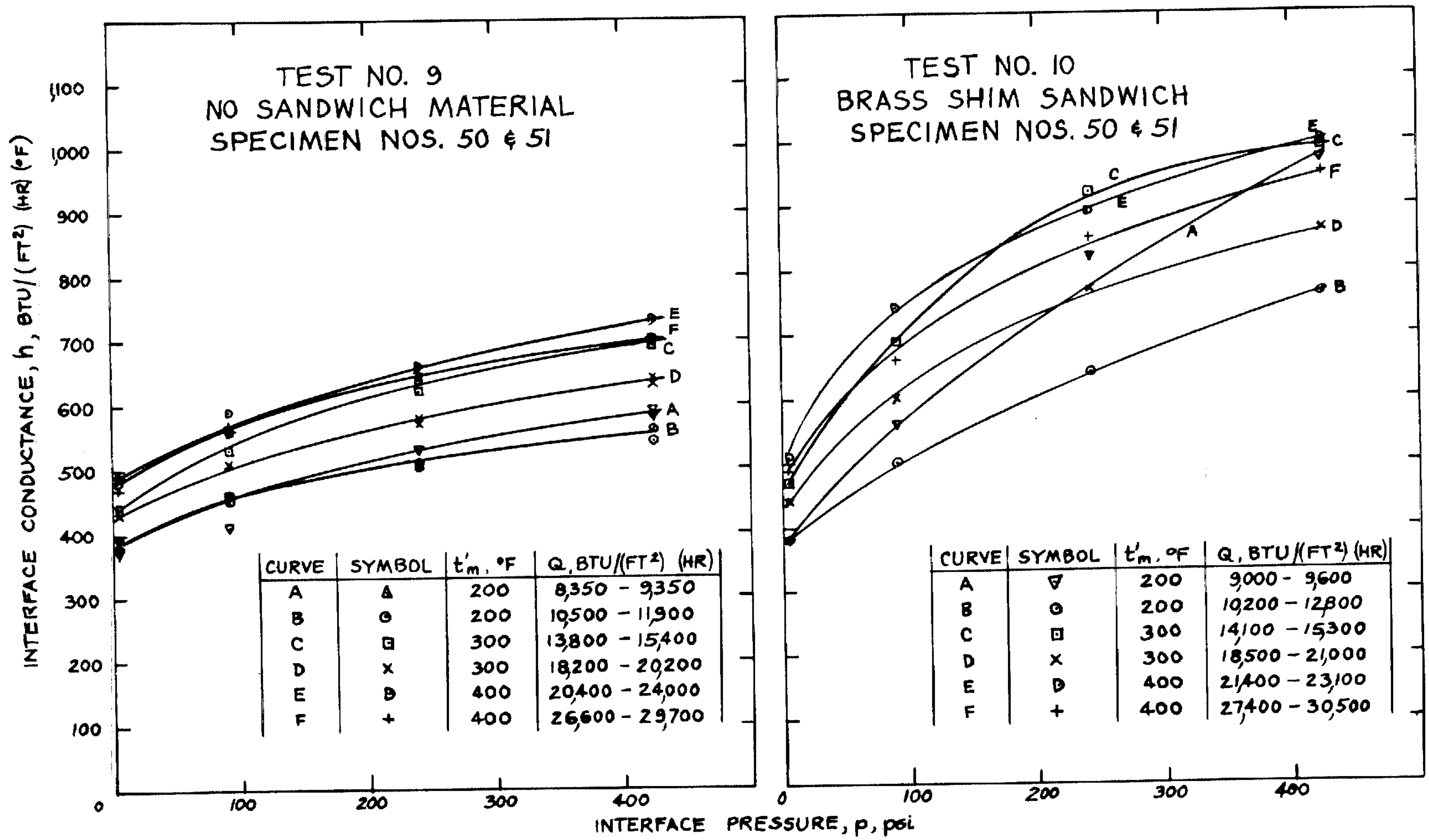
(e) Test 15, specimens 15 and 1; 75S-T6 aluminum-to-aluminum joint; 10- and 120-microinch root-mean-square surface roughness.

Figure 5.- Concluded.



(a) Comparative curves for 75S-T6 aluminum specimens with and without sandwich material; 120-microinch root-mean-square surface roughness.

Figure 6.- Effect of sandwich material on interface conductance at various interface pressures.



(b) Comparative curves for stainless steel specimens with and without sandwich material; 100-microinch root-mean-square surface roughness.

Figure 6.- Concluded.

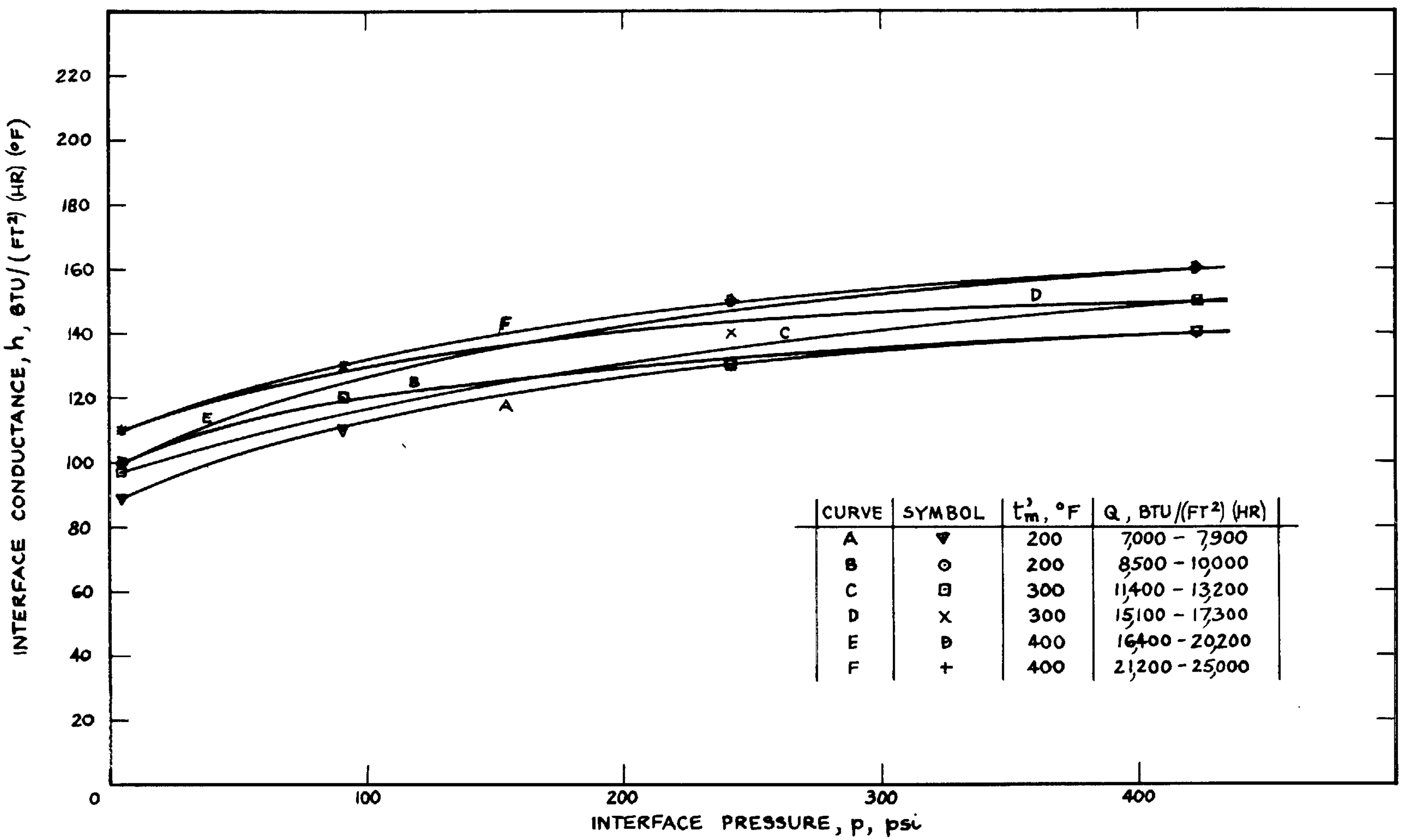
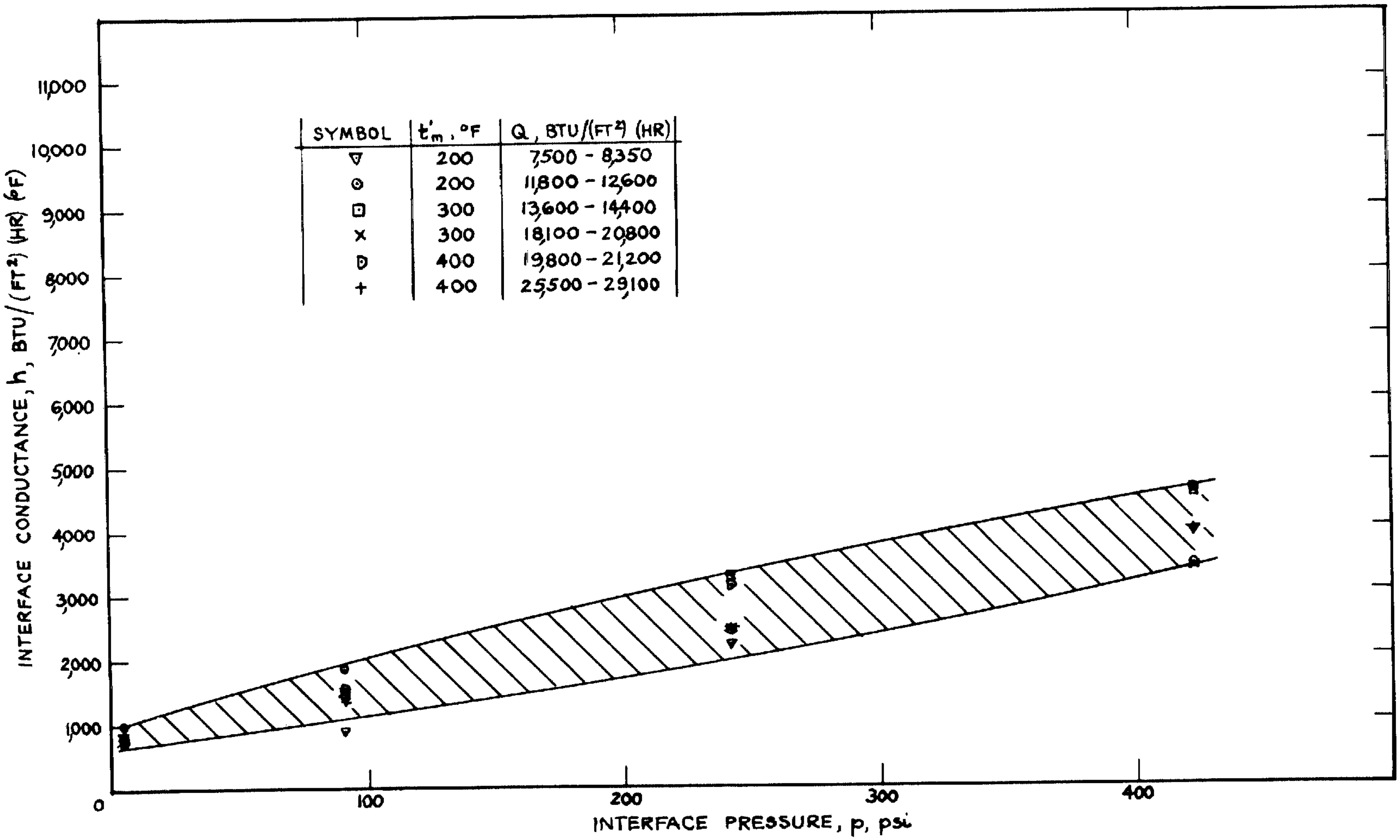
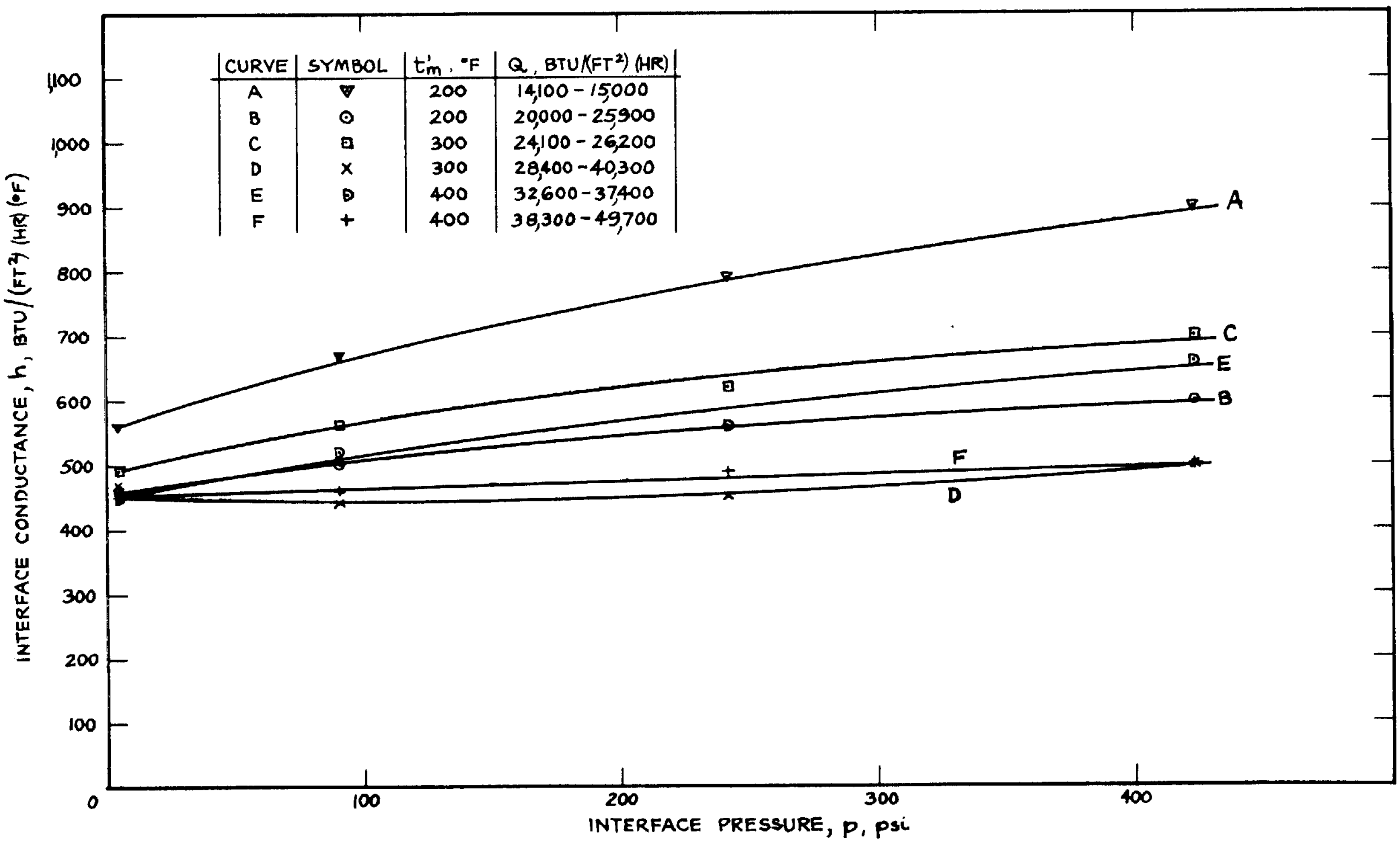


Figure 7.- Effect of asbestos-sheet sandwich material on interface conductance at various interface pressures. Test 11, specimens 50 and 51; joints of stainless steel to stainless steel; 100-microinch root-mean-square surface roughness.



(a) Flow from 75S-T6 aluminum specimen to stainless-steel specimen. Test 24, specimens 9 and 29.

Figure 8.- Effect of direction of heat flow on interface conductance at various pressures.



(b) Flow from stainless-steel specimen to 75S-T6 aluminum specimen. Test 22, specimens 49 and 9.

Figure 8.- Concluded.

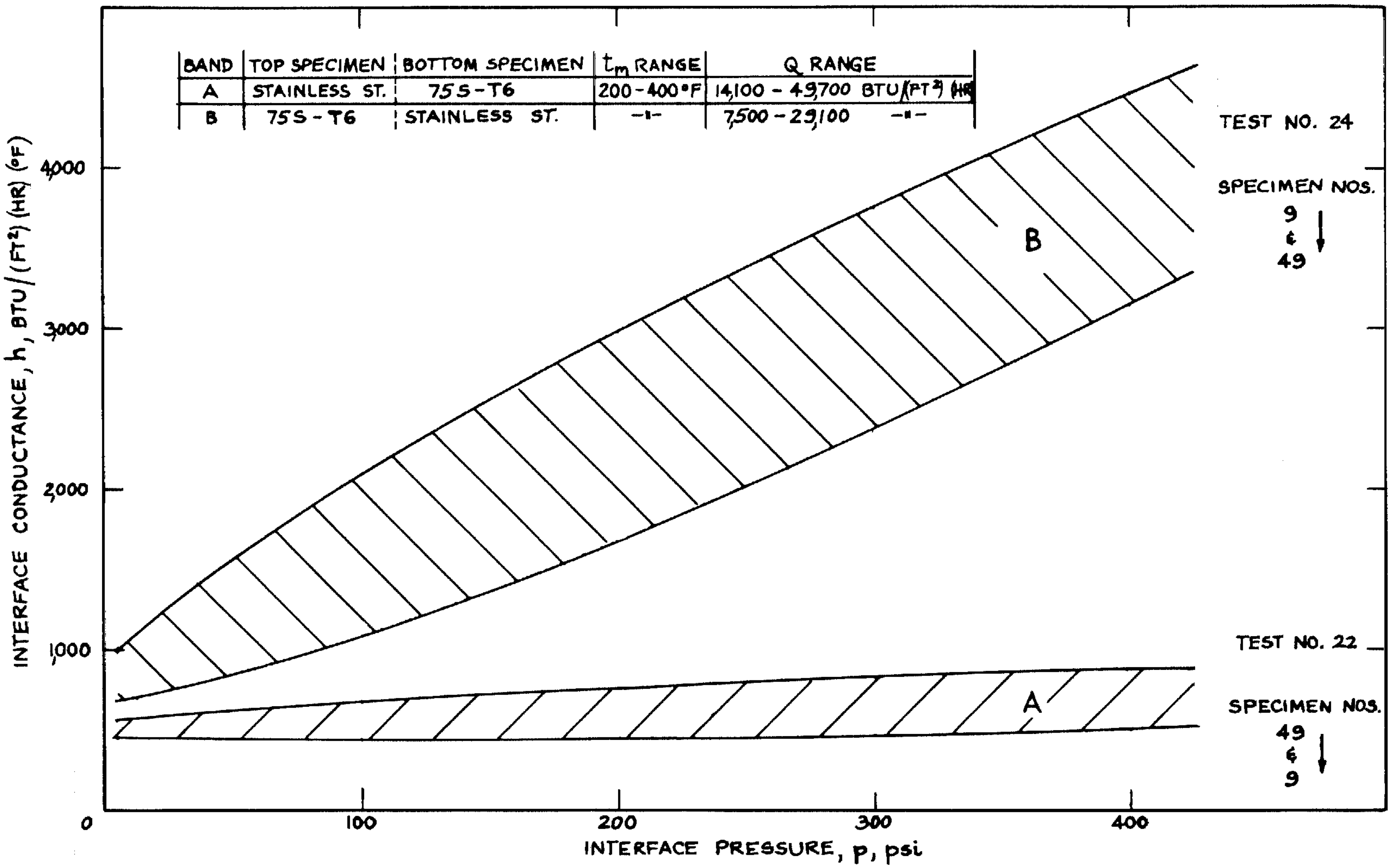


Figure 9.- Comparison of effects of heat-flow direction on interface conductance at various interface pressures.

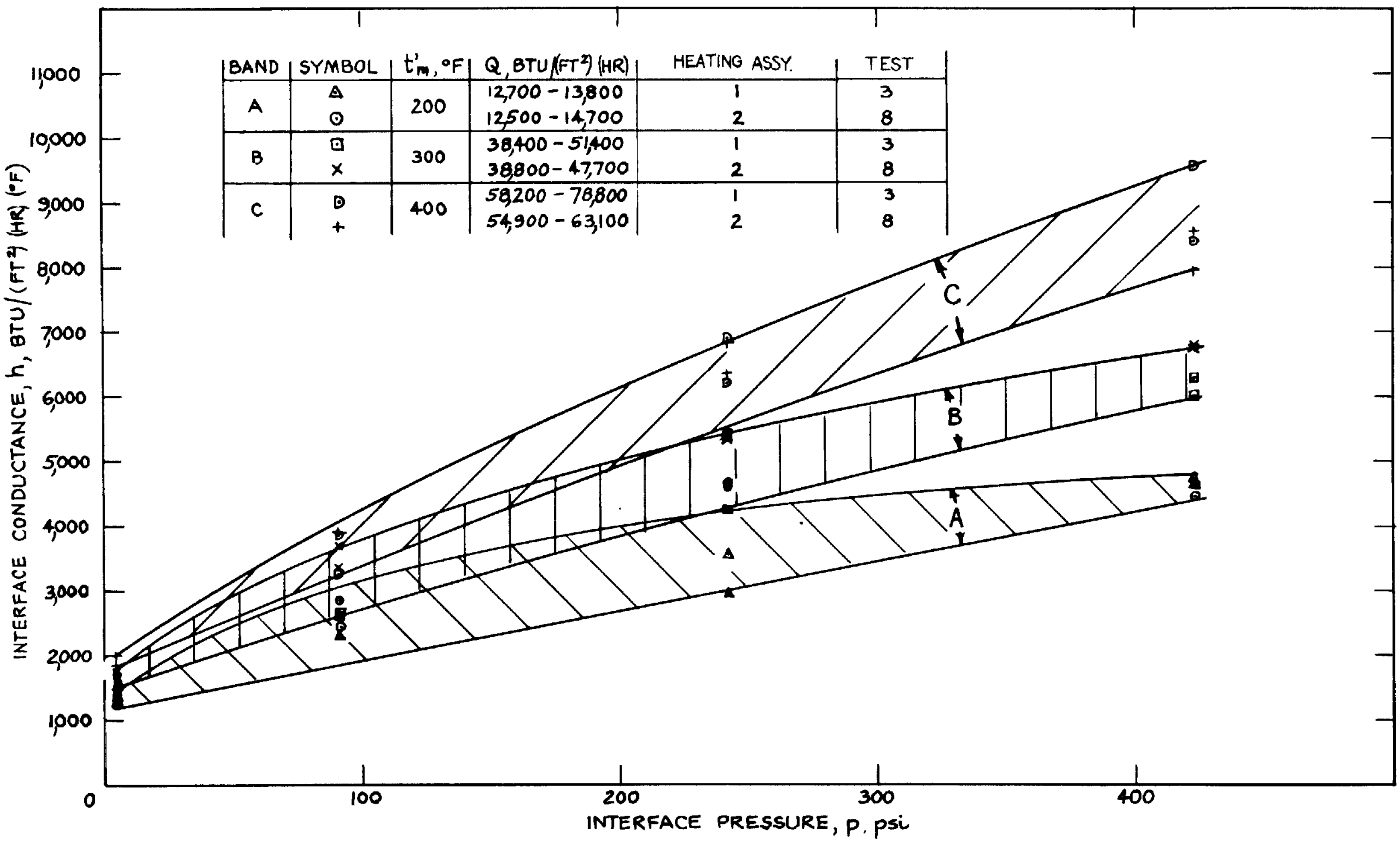
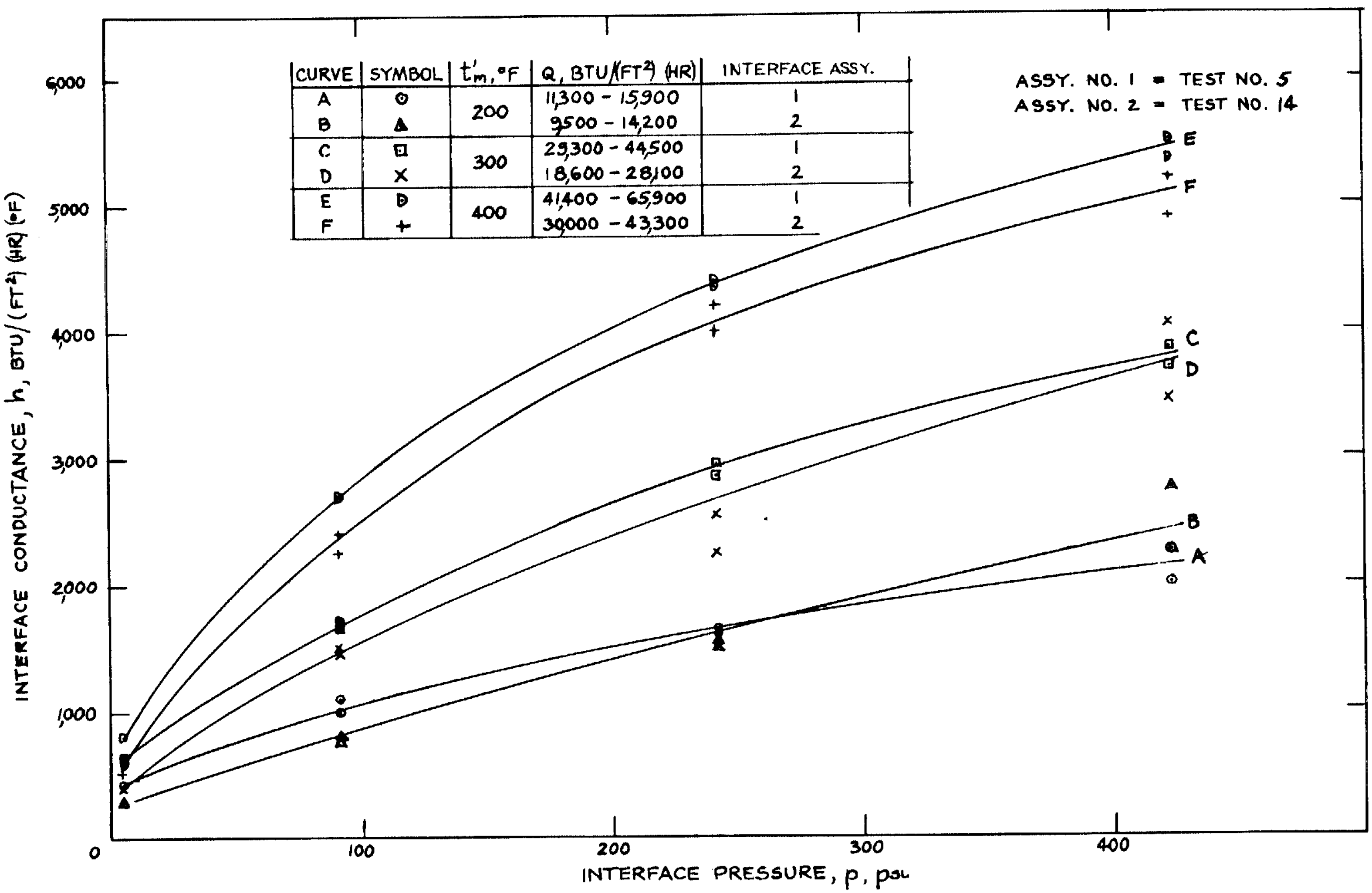
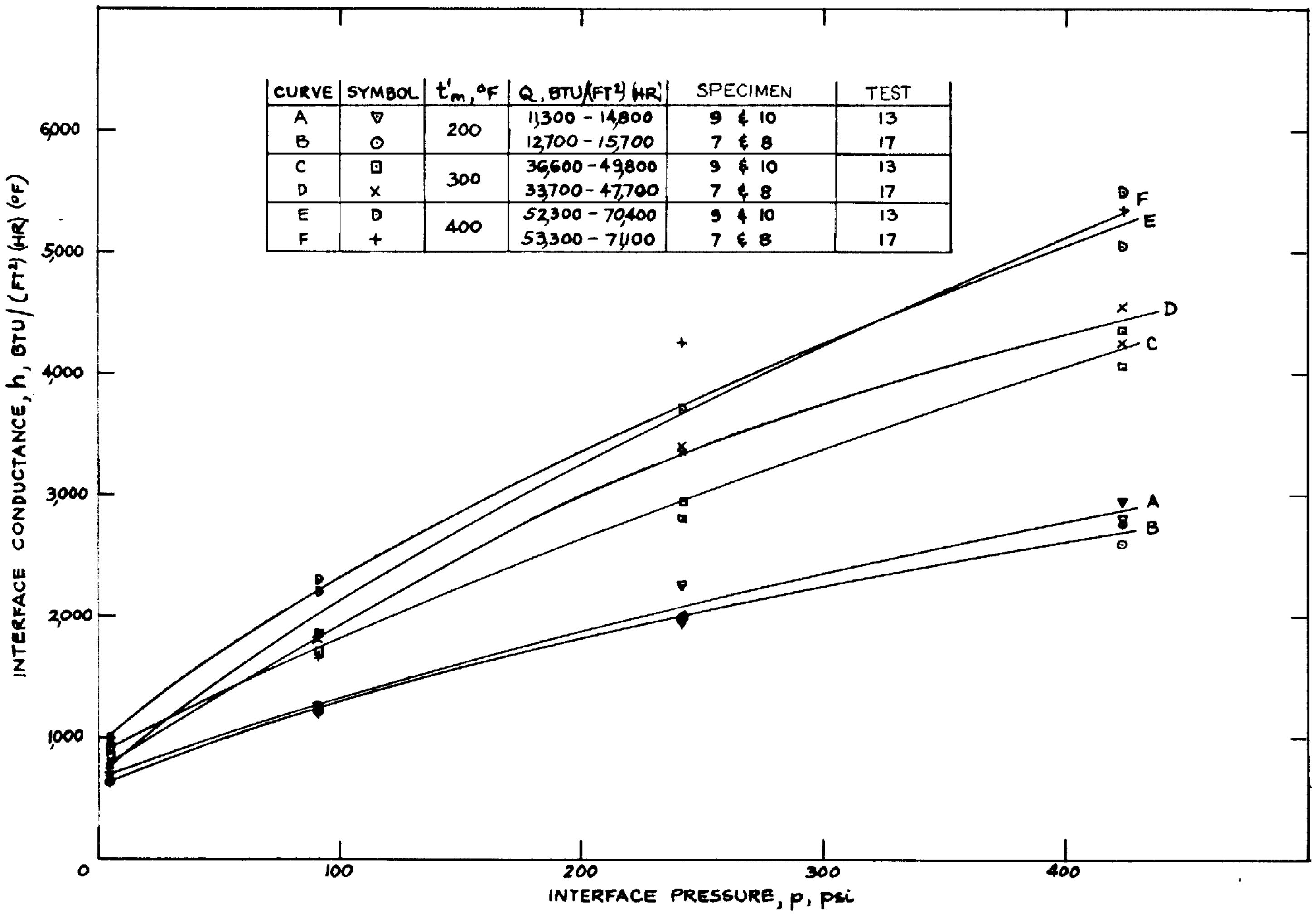


Figure 10.- Variation of interface conductance versus interface pressure due to reassembly of test apparatus without disturbance of interface matching. Specimens 15 and 16; 10-microinch root-mean-square surface roughness; 75S-T6 aluminum-to-aluminum joints.



(a) New heating and interface assembly, same specimens; 75S-T6 aluminum-to-aluminum joints; 120-microinch root-mean-square surface roughness.

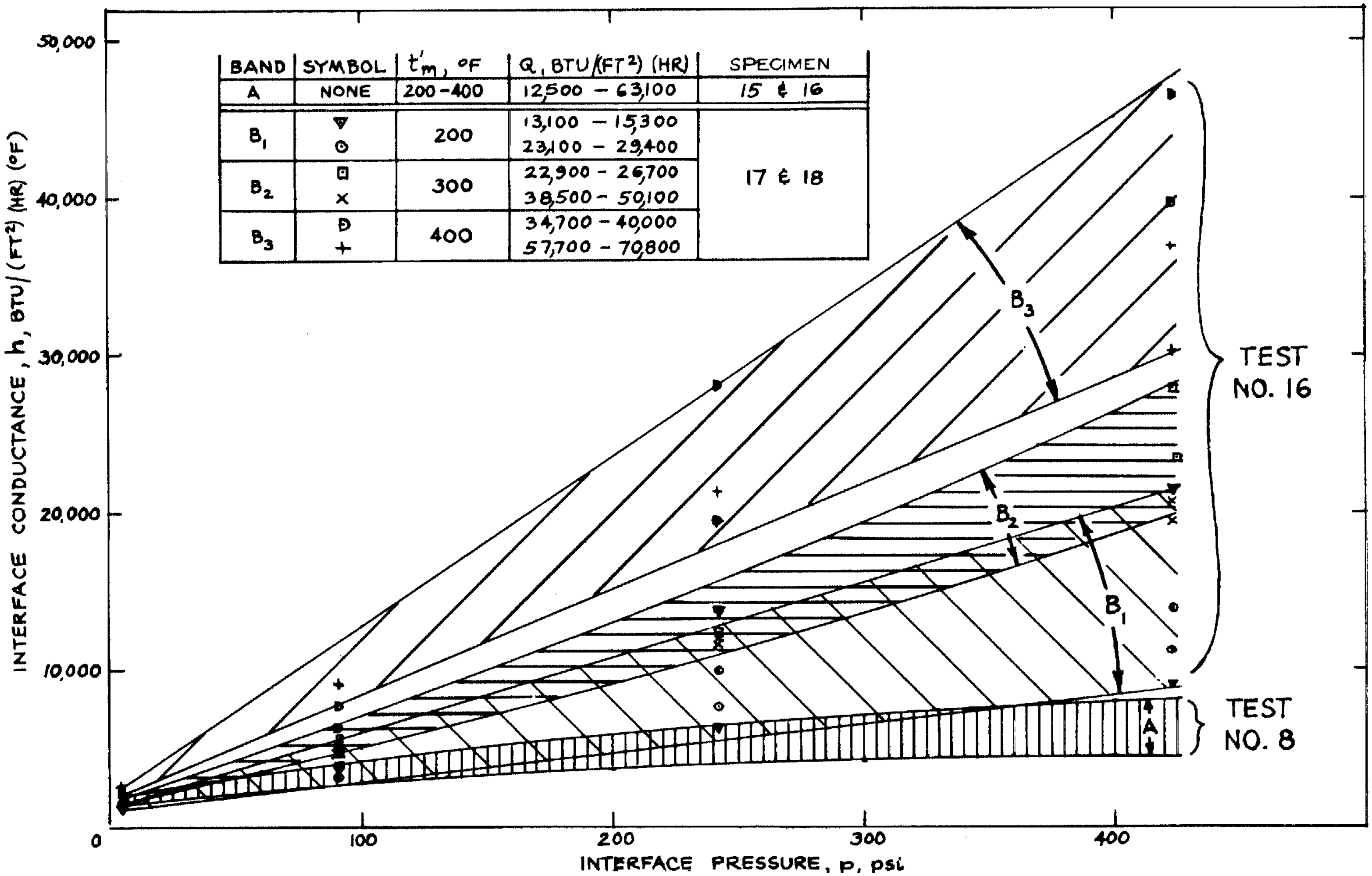
Figure 11.- Effect of surface matching on interface conductance at various interface pressures.



CURVE	SYMBOL	t'_m, °F	Q, BTU/(FT²)(HR)	SPECIMEN	TEST
A	▽	200	11,300 - 14,800	9 & 10	13
B	⊙		12,700 - 15,700	7 & 8	17
C	⊡	300	36,600 - 49,800	9 & 10	13
D	×		33,700 - 47,700	7 & 8	17
E	D	400	52,300 - 70,400	9 & 10	13
F	+		53,300 - 71,100	7 & 8	17

(b) New specimens, same surface roughness (65-microinch root-mean-square); 75S-T6 aluminum-to-aluminum joints.

Figure 11.- Continued.



BAND	SYMBOL	t'_m, °F	Q, BTU/(FT²) (HR)	SPECIMEN
A	NONE	200-400	12,500 - 63,100	15 & 16
B_1	▽ ⊙	200	13,100 - 15,300 23,100 - 29,400	17 & 18
B_2	⊡ ×	300	22,900 - 26,700 38,500 - 50,100	
B_3	D +	400	34,700 - 40,000 57,700 - 70,800	

(c) Exceptionally good matching, same surface roughness (10-microinch root-mean-square); 75S-T6 aluminum-to-aluminum joints.

Figure 11.- Concluded.